Digitized by the Internet Archive
in 2013

http://archive.org/details/researchpaper14paci_0

PUBLIC DOCUMENTS
DEPOSITORY ITEM

DEC [illegible]

CLEMSON
LIBRARY

PACIFIC SOUTHWEST
Forest and Range
Experiment Station

EST SERVICE
)EPARTMENT OF AGRICULTURE

ifteen-year growth patterns after thinning a ponderosa-Jeffrey pine plantation in northeastern California

William W. Oliver

CLEMSON UNIVERSITY LIBRARY
MAR 31 1980
SCI., TECH. & AGR. DIV.

RESEARCH PAPER PSW-141

The Author

WILLIAM W. OLIVER is doing silvicultural research on Sierra Nevada conifer types with headquarters at Redding, California. He earned a Bachelor of Science degree (1956) in forestry from the University of New Hampshire, and a Master of Forestry degree from the University of Michigan (1960). A native of Pennsylvania, he joined the Station in 1962, after working for the Michigan Department of Natural Resources.

ACKNOWLEDGMENTS

I am indebted to personnel of the California Region, Forest Service, U.S. Department of Agriculture—especially the timber management staff of the Modoc National Forest—for installing and maintaining the study plots upon which this report is based.

Fifteen-year growth patterns after thinning a ponderosa-Jeffrey pine plantation in northeastern California

William W. Oliver

CONTENTS

	Page
Introduction	1
Study Area	1
Methods	2
Growth Patterns	3
Diameter	3
Basal Area	6
Height	7
Volume	8
Conclusions	9
Literature Cited	9

Pacific Southwest Forest and Range Experiment Station
P.O. Box 245
Berkeley, California 94701

May 1979

IN BRIEF...

Oliver, William W.
1979. **Fifteen-year growth patterns after thinning a ponderosa-Jeffrey pine plantation in northeastern California.** Res. Paper PSW-141, 10 p., illus. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

Retrieval Terms: Pinus ponderosa, Pinus jeffreyi, thinning response, diameter growth, basal area, increment, stocking level, plantations, Modoc National Forest.

In a pole-size ponderosa and Jeffrey pine plantation, the Modoc National Forest thinned trees on six unreplicated plots to a wide range of stand densities. Measurements of growth patterns over the 15 years since thinning provide a rare opportunity to evaluate the current practice of making one precommercial thinning in such stands.

The plantation, on the west slope of the Warner Mountains in extreme northeastern California, has a site index of 50 feet (15 m) at 50 years, on the average. Trees were planted to an 8-foot (2.4-m) spacing in 1932. Survival after six growing seasons was 80 percent. Plots were thinned between 1959 and 1961 when the stand was 28 to 30 years old, 6 inches (15 cm) in diameter, and 18 feet (5 m) tall. After about 15 years, mean annual growth during each of three periods of about 5 years was analyzed.

Considered on this basis, periodic annual diameter growth was influenced markedly by thinning and the subsequent buildup of stand basal area. As basal area increased from 13 square feet to 147 square feet per acre (3.0 to 33.7 m²/ha), diameter growth decreased at a decreasing rate from 0.5 to 0.1 inch (1.3 to 0.3 cm) per year. Basal area growth, however, was linearly related to stand basal area and differed among growth periods. Annual growth during the first period ranged from 2 square feet per acre (0.46 m²/ha) in the most heavily thinned plot to 6.5 square feet (1.49 m²/ha) in the unthinned plot. In plots lightly thinned, it tended to be less during the second period and was significantly less during the third period for a given stand density. Most likely, growth declined because the plantation had passed the age when periodic annual basal area growth culminates.

Periodic annual height growth was associated with stand density. The average tree in plots heavily thinned grew more rapidly in height than the average tree in plots unthinned or thinned lightly, especially during the third period. Apparently, response was delayed until the released trees built up their crowns sufficiently to produce the additional food required for increased height growth.

Volume production levels rose rapidly with higher plot basal areas up to about 76 cubic feet per acre (5.32 m³/ha) at 70 square feet of basal area per acre (16.1 m²/ha). Production levels on plots with basal areas of above 70 square feet rose less rapidly to about 97 cubic feet per acre (6.79 m³/ha) annually at 110 square feet (25.2 m²/ha), and then remained virtually static. A basal area of 110 square feet per acre (25.2 m²/ha) seems optimum for timber production in this plantation since it represents nearly maximum volume production on the minimum amount of growing stock.

Standing merchantable volume built up rapidly on all plots over the 15 years of growth. Ingrowth was the major contributor during the first period and then declined in importance. Board-foot production was highest at a constant stand density during each period only when density was expressed as number of trees per acre rather than basal area. Production levels were highest at between 200 and 300 trees per acre (494 to 741 trees/ha)—about the optimum density for cubic volume production, also.

The performance of this ponderosa and Jeffrey pine plantation over about a 15-year period can be projected to evaluate a common thinning practice. I predict that 25 years after this plantation of 7-inch (17.8 cm) d.b.h. trees was thinned, it should reach a merchantable size of 12 inches (30.5 cm) with a basal area of 126 square feet per acre (28.9 m²/ha). A commercial thinning from below could yield 1200 board feet per acre of trees 9 to 12 inches (22.9 to 30.5 cm) and leave the stand at optimum density for continued volume production.

Most forest managers plan only one precommercial thinning in ponderosa pine or Jeffrey pine plantations in California. They hope that one thinning will be adequate until the trees reach sawlog size, when the merchantable material removed will pay for thinning and provide a return on investment. Recommendations of stand densities to meet this objective are based upon meager experience and research results, however. Thinning in plantations or in natural stands to the wider spacings now being practiced has not yet provided information on long-term growth trends. Most research on stand density reports short-term growth responses or is based on frequent rethinnings rather than only one.

An unusual opportunity to evaluate the practice of a single precommercial thinning occurred when the Modoc National Forest established six plots in a plantation of pole-size ponderosa and Jeffrey pine for thinning to a wide range of stand densities. This paper reports growth patterns on these plots after about 15 years. Measurements taken at periods of approximately 5 years were analyzed, and relationships of periodic annual increments in diameter, height, basal area, and cubic volume to stand density and years since thinning were determined.

STUDY AREA

The plantation is at 5400-feet (1647-m) elevation on the west slope of the Warner Mountains, 27 miles (43 km) northeast of Alturas, Modoc County, California. The plots lie on flat land or gentle north-facing slopes at the base of Sugar Hill. The soil is classified as Gleason gravelly sandy loam, an Entic Haploxeroll (U.S. Dep. Agric. Soil Conserv. Serv. 1975) confined principally to the Warner Mountains. Depth to a lithic contact of hard tuff is 40 to 60 inches (102 to 152 cm). The average annual precipitation of 22 inches (559 mm) falls mostly outside the growing season. Site index varies somewhat among plots *(table 1)* but on the average is 50 feet (15 m) at 50 years (Powers and Oliver 1978).

Trees were hand planted to an 8- by 8-foot (2.4- by 2.4-m) spacing in April 1932, 3 years after a wildfire devastated a natural stand of ponderosa pine *(fig. 1)*. The site was not prepared except that merchantable killed trees were logged. Stock was 1-1 ponderosa and Jeffrey pine grown from seed from an unknown location but probably collected in northeastern California.

Early survival and growth were good for those days *(fig. 1)*. After six growing seasons, 80 percent of the ponderosa pines and 66 percent of the Jeffrey pines were surviving. Ponderosa pine had grown to 32 inches (81 cm) and Jeffrey pine to 16 inches (39 cm) in height. By 1959, when thinning began, the plantation was 28 years old, 6 inches (15 cm) in diameter at breast height

Table 1—*Stand characteristics (acre basis) after thinning of ponderosa and Jeffrey pines in the Sugar Hill Plantation*

Plot and year established		Area	Site index (50 yr)	Trees	Growth periods analyzed			Avg. d.b.h.	Avg. height	Basal area	Total[1] volume	Merch.[2] volume
					1	2	3					
		Acres	*Feet*			*Years*		*Inches*	*Feet*	*Sq. ft.*	*Cu. ft.*	*Bd. ft.*
1	1959	1.36	55	43	7	4	5	7.4	23	13	103	39
2	1959	2.00	55	81	7	4	5	7.5	23	25	199	58
3	1960	1.00	50	100	6	4	5	6.7	21	24	179	17
4	1961	0.75	45	200	5	4	5	7.8	23	66	539	263
5	1960	1.00	55	300	6	4	5	7.2	21	86	647	154
Control	1960	1.00	45	456	6	5	4	5.5	16	75	436	10

[1] Inside bark from 1-foot stump to tip.

[2] Scribner board feet to a 6-inch top inside bark and 8-foot minimum log length; that is, most trees 9 inches d.b.h.o.b. and larger.

CLEMSON UNIVERSITY LIBRARY
DOCUMENTS DEPT.

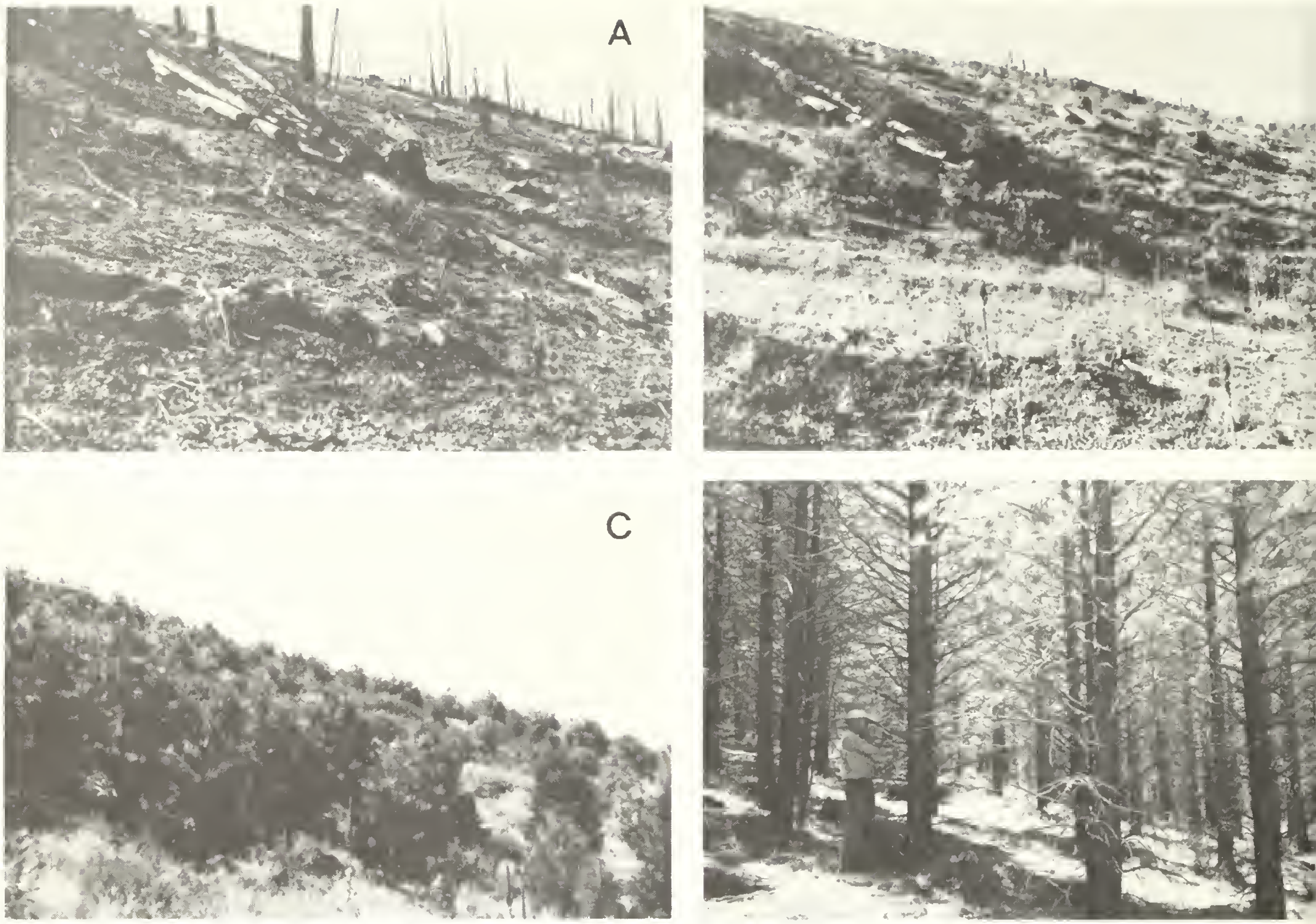


Figure 1—The Sugar Hill Plantation control plot is shown (A) in the fall of 1932 after planting; (B) 5 years later in the fall of 1936; (C) at 10 years of age in the fall of 1941; and (D) at 39 years of age in the spring of 1972.

and 18 feet (5 m) tall. All plots contained a scattered understory of rabbitbrush *(Chrysothamnus* sp.), big sagebrush (*Artemisia tridentata* Nutt.) and snowbrush (*Ceanothus velutinus* Dougl. ex Hook.). About 15 years later, brush remained scattered and, in general, inversely proportional to the overstory density.

METHODS

The six plots were thinned to a wide range of stand densities—13 to 86 square feet of basal area per acre (3.0 to 19.7 m^2/ha). Originally, plots varied in size from 1 to 2 acres (0.4 to 0.8 ha). Later, two plots had to be made smaller—plot 1 because it lacked an isolation strip and plot 4 because it was partially destroyed for construction of a fuel break *(table 1)*.

All plots were thinned outside the growing season by the usual standard; that is, the most vigorous well-formed dominants and codominants were selected as leave trees, as far as this was compatible with reasonably uniform spacing. Slash was lopped and scattered on all plots. Later, the felled boles were removed from those portions near roads by fuelwood gatherers.

All leave trees were tagged and measured immediately after thinning and remeasured at three intervals of about 5 years thereafter *(table 1)*. At each measurement, diameters at breast height for all trees were recorded to the nearest 0.1 inch (0.25 cm) and heights for every fifth tree to the nearest foot (0.3 m).

At the end of the third period, 6 to 10 trees in each plot were chosen so that probabilities were proportional to estimated size for stem volume determinations. Upper stem diameters and lengths were measured with an optical dendrometer. Stem volumes inside bark, in cubic feet and board feet, Scribner, were calculated by Grosenbaugh's (1974) STX computer program as modified by Space (1974).

When these volumes (both cubic and board foot measures) were plotted over the product of diameter squared times total height (D^2H), no differences among volumes of trees in plots thinned to different basal areas could be found. Therefore, the following equations weighted by $1/D^2H$ and solved by least squares were considered adequate for all plots:

$$\begin{aligned} Vol_T &= -0.08123 + 0.00193\, D^2H \\ S_{y.x} &= 0.0112 \\ Vol_{BF} &= -11.55734 + 0.00734\, D^2H \\ S_{y.x} &= 0.0910 \end{aligned}$$

in which

Vol_T = stem volume in cubic feet inside bark from 1-foot (0.3-m) stump to tip
D^2H = d.b.h.^{2} in inches times total height in feet
Vol_{BF} = merchantable stem volume in board feet, Scribner, to a 6-inch (15-cm) top inside bark and a minimum log length of 8 feet (2.4 m)—that is, most trees 9 inches (23 cm) d.b.h.o.b. and larger
$S_{y.x}$ = sample standard deviation from regression

The total height of all trees had to be estimated to calculate plot volumes. Since growth was to be analyzed over three growing periods, a single equation for each plot, expressing height as a function of both diameter and age, was expected to yield more accurate and consistent estimates than individual height/diameter curves would yield for each measurement. Scatter diagrams of height over diameter, combining data for all three periods, were prepared for each plot. A visual inspection of these diagrams suggested that one equation would describe adequately the height/diameter relationship of trees in plots 4 and 5, and the control (thinned to 200 or more trees per acre [494 trees/ha]). And another equation would describe adequately trees in plots 1, 2, and 3 (thinned to 100 or fewer trees per acre [247 trees/ha]). A multiple regression equation suggested by Curtis (1967) was fitted to each group of plots by a stepwise regression procedure, retaining the most significant terms. The following equations resulted for plots 4 and 5, and the control:

$$\begin{aligned} H &= 1.26695 + 0.34513\,(ln D)\,(ln A) - 0.02136\,(ln D)\,(ln A)^2 \\ S_{y.x} &= 0.128 \end{aligned}$$

and for plots 1, 2, and 3:

$$\begin{aligned} H &= 5.37368 - 0.49461\,(ln D)^2 - 0.50800\,(ln A)^2 + 0.24218\,(ln D)\,(ln A)^2 \\ S_{y.x} &= 0.113 \end{aligned}$$

in which

H = total height in feet
$ln D$ = natural logarithm of d.b.h. in inches
$ln A$ = natural logarithm of age since planting

Stand characteristics after thinning and after three subsequent growth periods are presented in *table 1* on an acre basis.

GROWTH PATTERNS

Mean annual growth during each of the three periods of about 5 years was analyzed. Periodic annual growth of most tree and stand characteristics was found to be related to stand density and, sometimes, to growth period also *(table 2)*.

Diameter

Periodic annual diameter growth was influenced markedly by thinning and the subsequent buildup of stand basal area. Growth was most rapid—0.5 inch (1.3 cm) per year—during the first period after thinning on the most heavily thinned plot. Growth was slowest—0.1 inch per year—during the third period in the unthinned control plot. As basal area increased, periodic annual diameter growth decreased at a decreasing rate *(fig. 2A)*. This curvilinear relationship was similar for all periods and can be expressed by the equation:

$$PAI\ DBH = 0.82677 - 0.13740\, ln BA$$

in which

$PAI\ DBH$ = periodic annual increment in diameter in inches
$ln BA$ = natural logarithm of basal area in square feet per acre

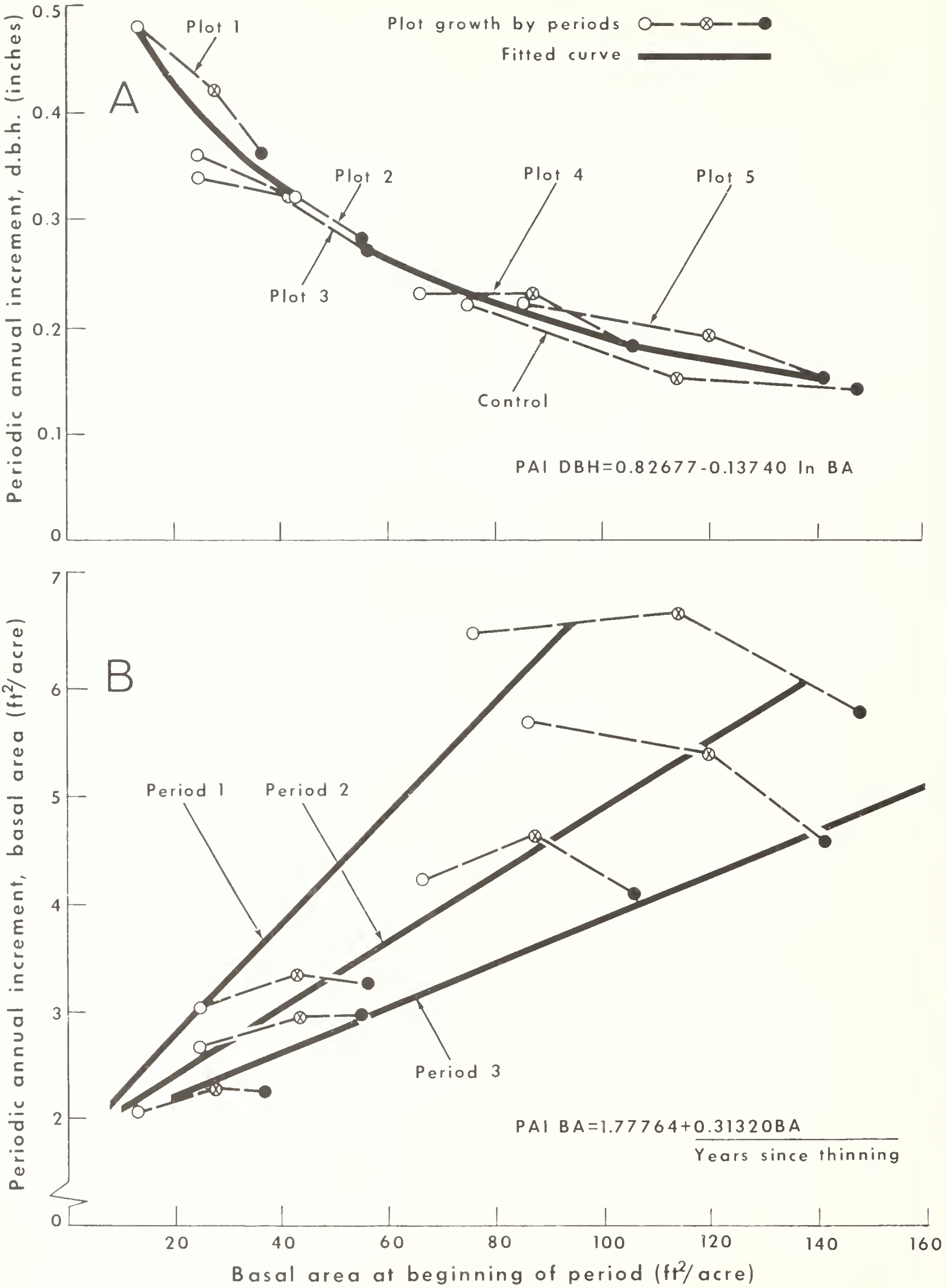


Figure 2—Fifteen years after thinning ponderosa and Jeffrey pine poles in the Sugar Hill Plantation, periodic annual increment (PAI) was determined for each of three periods of about 5 years. (A) The pattern of smaller diameter increment in plots with greater basal area was similar during all periods. (B) Basal area increment was greater with larger stand basal area but less with time since thinning.

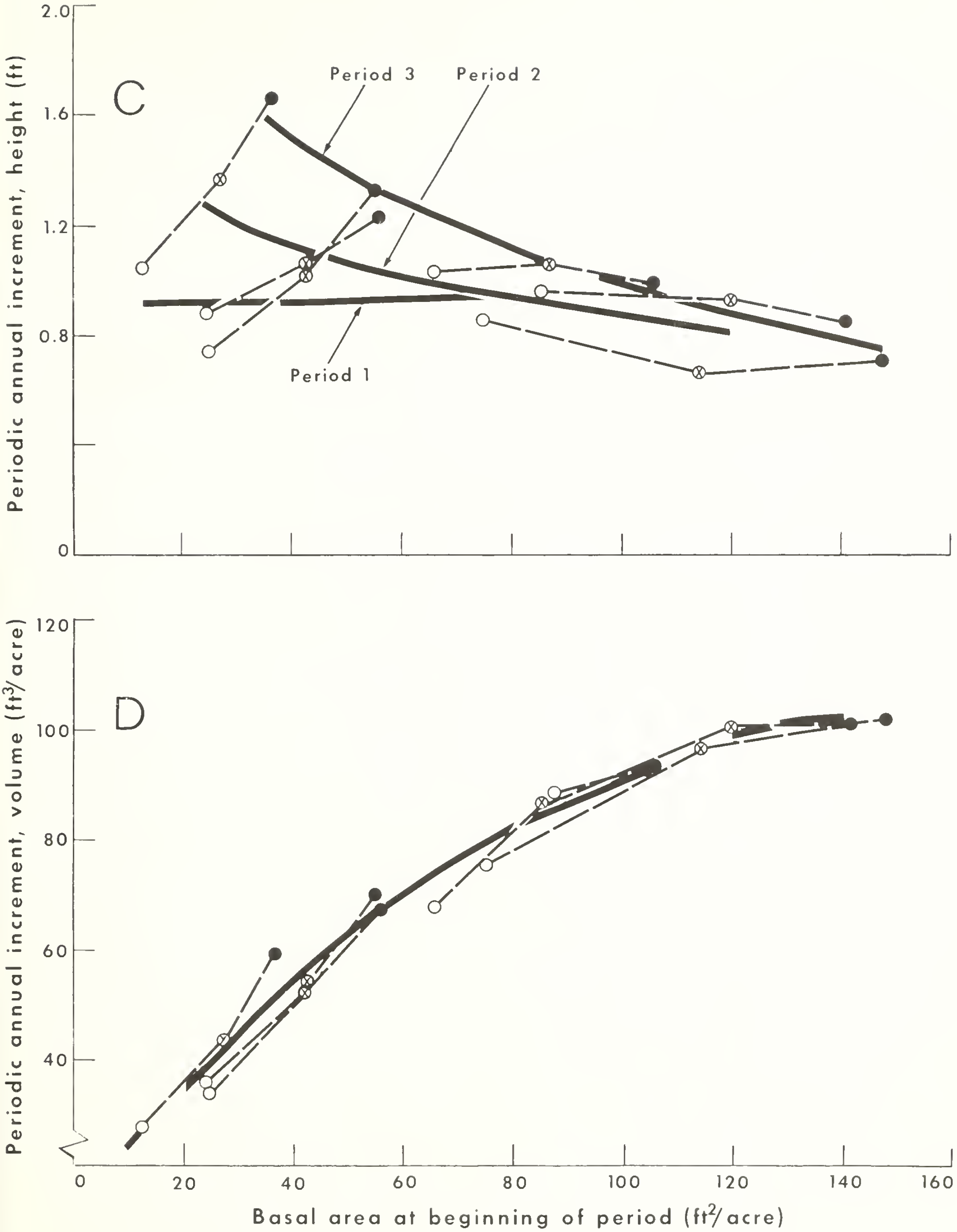


Figure 2 (continued) (C) Height increment was greater in plots wih lower basal areas during the second and third periods, only. (D) The pattern of more total volume increment in plots with greater basal area was similar during all periods.

Table 2—*Periodic annual growth (acre basis) for three growth periods after thinning ponderosa and Jeffrey pine poles in the Sugar Hill Plantation*

Plot	Stand density at beginning of period		Periodic annual growth				
	Trees	Basal area	D.b.h.	Height	Basal area	Total[1] volume	Merch.[2] volume
		Feet^2	*Inches*	*Feet*	*Sq. ft.*	*Cu. ft.*	*Bd. ft.*
			First period				
1	43	13	0.5	1.0	2.0	27	87
2	81	25	.3	0.7	2.6	34	107
3	100	24	.4	0.9	3.0	36	71
4	200	66	.2	1.0	4.2	68	192
5	300	86	.2	1.0	5.7	85	180
Control	456	75	.2	0.8	6.5	76	38
			Second period				
1	43	27	0.4	1.4	2.3	43	164
2	81	43	.3	1.0	2.9	53	199
3	100	43	.3	1.0	3.3	53	184
4	200	87	.2	1.0	4.6	88	316
5	300	120	.2	0.9	5.4	100	348
Control	456	114	.2	0.7	6.7	98	174
			Third period				
1	43	36	0.4	1.7	2.3	59	222
2	81	55	.3	1.3	2.9	70	264
3	100	56	.2	1.2	3.2	68	255
4	200	106	.2	1.0	4.1	94	351
5	299	141	.2	0.8	4.6	101	376
Control	477	147	.1	0.7	5.7	102	289

[1] Inside bark from 1-foot stump to tip.

[2] Scribner board feet to a 6-inch top inside bark and 8-foot minimum log length, that is, most trees 9 inches d.b.h.o.b. and larger.

The influence of basal area is highly significant ($P \leq 0.01$), explaining 95 percent of the variation in periodic annual diameter increment among plots and periods.

By the end of the third growth period or about 15 years after thinning, diameters were distributed as shown in *figure 3*.

Basal Area

Basal area growth was linearly related to stand basal area and differed among growth periods (*fig. 2B*). Periodic annual basal area growth was most rapid for a given stand density during the first period. It ranged from 2.0 square feet per acre (0.46 m^2/ha) in the most heavily thinned plot to 6.5 square feet (1.49 m^2/ha) in the unthinned plot. Basal area growth tended to be less for a given stand density during the second period, but covariance analysis revealed no statistically significant difference.

During the third period, however, basal area growth dropped significantly from that of the second period. The most heavily thinned plot grew 2.3 square feet (0.53 m^2/ha) per year. Basal area growth increased with higher stand densities, reaching 5.7 square feet (1.31 m^2/ha) per year in the unthinned plot.

In general, basal area growth dropped more in succeeding periods in plots unthinned and lightly thinned than it did in plots heavily thinned. These patterns of

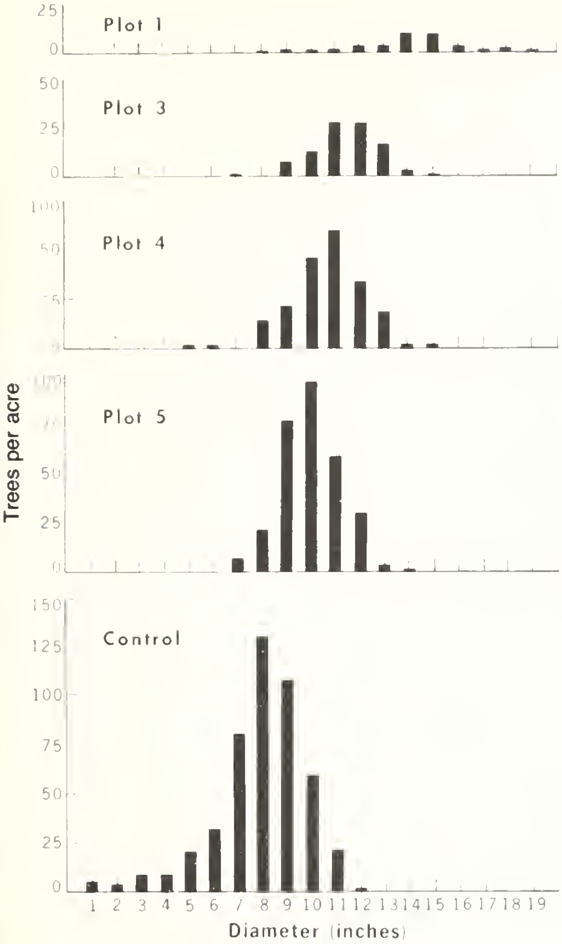


Figure 3—Diameter distributions of plots in the Sugar Hill Plantation 15 years after thinning to five different densities. (Plot 2, not shown, was thinned to about the same density as Plot 3.)

basal area growth following thinning can be combined in the following single expression:

$$\text{PAI BA} = 1.7776 + 0.31320X$$

in which

PAI BA = periodic annual basal area increment in square feet per acre

X = the quotient of stand basal area in square feet per acre at the beginning of the growth period divided by the number of years since thinning

The independent variable explained 79 percent of the variation in basal area growth.

The marked difference among periods in the relation of basal area growth to stand basal area has a possible explanation. The plantation at time of thinning had passed the age when basal area growth is most rapid (Oliver and Powers 1978). On the average, ponderosa pine plantations growing at a density of 370 trees per acre (914 trees per ha) produce 5.4 square feet (1.24 m^2/ha) of basal area annually between the ages of 25 and 30 years on locations having site qualities similar to that of Sugar Hill. Growth drops to 4.8 square feet (1.10 m^2/ha) annually between stand ages of 35 and 40 years. These rates are only slightly lower than those found in the Sugar Hill study for the unthinned and most lightly thinned plots. Trees on these plots grew 6.1 square feet per acre (1.40 m^2/ha) annually between stand ages of 28 and 34, and 5.1 square feet (1.17 m^2/ha) annually between the ages of 38 and 43, on the average.

Height

The relation of periodic annual height growth to stand density following thinning is complex. Height growth response often is delayed 3 or 4 years until the released trees build up their crowns sufficiently to produce the additional food required for increased height growth.

In the Sugar Hill study this delayed response was striking. Height growth over the entire period of about 15 years was not related significantly to post-thinning stand density. But when regressions of periodic annual height growth were calculated for each of the three periods, an increasing response with time since thinning was revealed (*fig. 2C*). No relation between stand basal area and height growth existed during the first period—trees in all plots grew 0.9 foot (0.27 m) per year, on the average. During the second period, trees in the three plots most heavily thinned grew faster in height—up to 1.4 feet (0.43 m) per year—whereas height growth in the unthinned and two lightly thinned plots dropped slightly. This trend, though evident, was not statistically significant. During the last period, however, height growth was significantly related to stand basal area. Growth rate of trees in the three heavily thinned plots continued to increase, up to 1.7 feet (0.52 m) per year. Growth rate of trees in the unthinned plots and in the two lightly thinned plots declined again—this time to 0.8 foot (0.24 m) per year.

This delay in height growth response to thinning can be inferred from reports of other thinning studies in ponderosa pine. Barrett (1963, 1968) found no significant response from thinning studies in pole-size ponderosa pine on comparable sites in the Pacific Northwest; neither did Schubert (1971), reporting on a thinning study in pole-size ponderosa pine on a slightly poorer site in northern Arizona. These three reports were based on the first 5 or 6 years following thinning of dense natural stands. When height growth has been followed for longer periods, most investigators report a marked response (Stage 1958; Myers 1958; Boldt 1970).

Volume

Cubic Volume

Periodic annual cubic volume growth was closely related to stand basal area during each of the three periods. When each period was analyzed separately, the relationships were positive and linear; the rate of increase in volume growth with increasing basal area slowed with each succeeding period. Only when all periods were combined for analysis (18 observations) did a full picture of the relation between stand density and cubic volume production emerge *(fig. 2D)*. The relationship is similar for all three periods and departs significantly from linearity.

Volume production increased almost linearly with accumulating basal area to about 76 cubic feet per acre (5.32 m³/ha) at 70 square feet of basal area per acre (16.1 m²/ha). The rate of increase began to slacken at higher stand basal areas, reaching about 97 cubic feet per acre (6.79 m³/ha) annually at 110 square feet per acre (25.2 m²/ha). Cubic volume production remained virtually static at basal areas above 110 square feet per acre (25.2 m²/ha). This stand density was optimum for timber production in this plantation since it represented nearly the maximum volume production on the minimum amount of growing stock.

The relation of cubic volume production to stand basal area is described best by the quadratic equation:

$$\text{PAI Vol} = 11.47631 + 1.20045X - 0.00396X^2$$
$$Sy.x = 3.705$$

in which

PAI Vol = periodic annual volume increment in cubic feet per acre

X = basal area in square feet per acre

Basal area explains 97 percent of the variation in cubic volume production in all plots over the period of about 15 years following thinning.

Although the curve for the quadratic equation *(fig. 2D)* fits best within the range of data, extrapolating growth to higher basal areas may create errors. The equation implies a drop in volume production above basal areas of 152 square feet per acre (34.9 m²/ha), but actual production may remain constant before dropping at a much higher basal area.

This estimate of volume production is 20 percent higher for plots lightly thinned than that reported earlier (Oliver 1972) after two growth periods. The earlier report included six plots in natural stands subsequently found to be on sites of lower productivity. Their inclusion caused volume production to be underestimated at Sugar Hill.

Board Feet

Standing merchantable volume built up rapidly on all plots during the 15 years. Ingrowth into merchantable sizes was the major contributor during the first period in all plots, and then declined in importance. Only in the unthinned plot during the third period was ingrowth important still.

At time of thinning, when the stand was about 28 years old, merchantable volume production was just beginning *(table 1)*. Only a few trees had reached the merchantable size of 9 inches d.b.h.o.b. (capable of producing an 8-foot log 6 inches in diameter inside bark at the small end—intensive utilization by today's standard). For example, the unthinned plot contained only 10 board feet per acre. Merchantable volume was highest (263 bd. ft/acre) in the plot thinned to 66 square feet of basal area per acre (15.2 m²/ha) because this plot contained trees with the largest average diameter after thinning.

Merchantable volume production was related to stand basal area within periods but differed markedly among periods because of differing tree size *(table 2)*. Within periods, board-foot production was highest in moderately thinned plots. In the unthinned plot, it dropped to about the level of plots heavily thinned.

Board-foot production was highest at a constant stand density during each period only when density was expressed as number of trees per acre rather than basal area. At 200 to 300 trees per acre (494 to 741 trees/ha) production reached 192 board feet per acre during the first period. Highest production level was 348 board feet during the second period and only slightly more, 376 board feet, during the third period, as ingrowth became inconsequential.

Fortunately, the stand density optimum for cubic volume production seems to be about optimum for board-foot production, also. At the beginning of the third period of growth, 200 to 300 trees per acre (494 to 741 trees/ha) produced 106 to 141 square feet of basal area per acre (24.3 to 32.3 m²/ha). Optimum basal area for cubic volume production was estimated to be 110 square feet (25.2 m²/ha).

CONCLUSIONS

The 15-year growth record after precommercial thinning of plots in the Sugar Hill Plantation provides an opportunity to evaluate a common thinning practice. Ponderosa and Jeffrey pine plantations usually are precommercially thinned once in the sapling or small pole-size classes to minimize cost, fire hazard, and growth loss from intertree competition until they reach merchantable size.

Thinning intensity is governed, primarily, by the manager's estimate of minimum merchantable size and minimum volume per acre that can be removed in a commercial thinning at some future date. Commercial low thinnings removing 1000 board feet per acre of trees 9 to 12 inches (22.9 to 30.5 cm) in diameter would seem to be profitable and common in the near future. Similar thinnings occasionally are being sold today under ideal conditions.

Optimum stocking levels and resulting stand performance can be predicted from the economic forecasts and thinning plot results. I estimate that 25 years will be required for the Sugar Hill Plantation to reach 12 inches in average stand diameter (yielding trees 9 to 12 inches in a low thinning) when thinned at 7 inches (17.8 cm) to a basal area of 50 square feet per acre (11.5 m^2/ha) or 160 trees per acre (395 trees /ha). Thus, at age 53, the plantation can be expected to have the following distribution of diameters on an acre:

D.b.h.:

Inches	Cm	*Trees*
8	20	2
9	23	6
10	25	15
11	28	30
12	30	47
13	33	33
14	36	20
15	38	6
16	41	1

Other characteristics would be as follows:

Basal area per acre:	126 square feet (28.9 m^2/ha)
Total volume per acre:	1800 cubic feet (125.9 m^3/ha)
Merchantable volume per acre:	5300 board feet

A commercial thinning from below seems feasible at age 53 if we assume: (a) 110 square feet per acre (25.2 m^2/ha) as optimum leave stand density, (b) annual growth of 3.5 square feet of basal area per acre (0.80 m^2/ha), and (c) a commercial thinning cycle of 10 years. A low thinning would remove 34 square feet per acre (7.8 m^2/ha) leaving 92 square feet of basal area per acre (21.1 m^2/ha)—an optimum density for continued volume production on a 10-year thinning cycle. About 1200 board feet of merchantable material per acre might thus be produced. These yields are similar to those predicted for natural stands of ponderosa pine on similar sites in the Pacific Northwest, where one thinning left the stand with an average diameter of 6 inches (Sassaman and others 1977).

Precommercial thinning of pole-size plantations as was done here is not recommended. One of the disadvantages stated previously is growth loss from intertree competition. If the Sugar Hill Plantation had been thinned as saplings to 160 trees per acre, merchantable size might have been reached 10 years sooner than age 53.

These growth projections are based upon one stand only. Specific growth rates may differ in other stands but the general relationships should be similar.

LITERATURE CITED

Barrett, James W.
1963. **Dominant ponderosa pines do respond to thinning.** U.S. Forest Serv. Res. Note PNW-9, 8 p., illus. Pacific Northwest Forest and Range Exp. Stn., Portland, Oreg.

Barrett, James W.
1968. **Response of ponderosa pine pole stands to thinning.** U.S. Forest Serv. Res. Note PNW-77, 11 p., illus. Pacific Northwest Forest and Range Exp. Stn., Portland, Oreg.

Boldt, Charles E.
1970. **Sequential thinnings boost productivity of a ponderosa pine stand in the Black Hills of South Dakota.** USDA Forest Serv. Res. Note RM-172, 7 p., illus. Rocky Mountain Forest and Range Exp.Stn., Fort Collins, Colo.

Curtis, Robert O.
1967. **Height-diameter and height-diameter-age equations for second-growth Douglas-fir.** Forest Sci. 13(4):365-375, illus.

Grosenbaugh, L.R.

1974. **STX 3-3-73: Tree content and value estimation using various sample designs, dendrometry methods, and V-S-L conversion coefficients.** USDA Forest Serv. Res. Paper SE-117, 112 p., illus. Southeastern Forest Exp. Stn., Asheville, N.C.

Myers, Clifford A.

1958. **Thinning improves development of young stands of ponderosa pine in the Black Hills.** J. For. 56(9):656-659, illus.

Oliver, William W.

1972. **Growth after thinning ponderosa and Jeffrey pine pole stands in northeastern California.** USDA Forest Serv. Res. Paper PSW-85, 8 p., illus. Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif.

Oliver, William. W., and Robert F. Powers.

1978. **Growth models for ponderosa pine: I. Yield of unthinned plantations in northern California.** U.S. Dep. Agric. Forest Serv. Res. Paper PSW-133, 21 p., illus. Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif.

Powers, Robert F., and William W. Oliver.

1978. **Site classification of ponderosa pine stands under stocking control in California.** U.S. Dep. Agric. Forest Serv. Res. Paper PSW-128, 9 p., illus. Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif.

Sassaman, Robert W., James W. Barrett, and Asa D. Twombly.

1977. **Financial precommercial thinning guides for northwest ponderosa pine stands.** USDA Forest Serv. Res. Paper PNW-226, 27 p., illus. Pacific Northwest Forest and Range Exp. Stn., Portland, Oreg.

Schubert, Gilbert H.

1971. **Growth response of even-aged ponderosa pines related to stand density levels.** J. For. 69(12):857-860, illus.

Space, James C.

1974. **3-P forest inventory, design, procedures, data processing.** State and Priv. For., Southeast Area, Forest Serv., U.S. Dep. Agric., Atlanta, Ga.

Stage, A.R.

1958. **Growth of thinned ponderosa pine in western Montana.** J. For. 56(10):757-760, illus.

U.S. Department of Agriculture, Soil Conservation Service.

1975. **Soil taxonomy.** U.S. Dep. Agric., Agric. Handb. 436, 754 p., illus.

Oliver, William W.
1979. **Fifteen-year growth patterns after thinning a ponderosa-Jeffrey pine plantation in northeastern California.** Res. Paper PSW-141, 10 p., illus. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

Growth was analyzed after one thinning in a plantation of pole-size ponderosa and Jeffrey pines on land having a site index of 50 feet at 50 years. Periodic annual increment was determined for each of three 5-year periods. On this basis, increment in diameter and cubic volume were found to be related closely to stand basal area only. Basal area and height increment, however, were also related to time since thinning; basal area growth decreased and height growth increased with each succeeding period. The optimum basal area for volume production (both cubic and board-foot measures) was estimated to be 110 ft²/acre. Optimum stocking levels and resulting stand performance are predicted for a common thinning practice.

Retrieval Terms: Pinus ponderosa, Pinus jeffreyi, thinning response, diameter growth, basal area, increment, stocking level, plantations, Modoc National Forest.

Oliver, William W.
1979. **Fifteen-year growth patterns after thinning a ponderosa-Jeffrey pine plantation in northeastern California.** Res. Paper PSW-141, 10 p., illus. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

Growth was analyzed after one thinning in a plantation of pole-size ponderosa and Jeffrey pines on land having a site index of 50 feet at 50 years. Periodic annual increment was determined for each of three 5-year periods. On this basis, increment in diameter and cubic volume were found to be related closely to stand basal area only. Basal area and height increment, however, were also related to time since thinning; basal area growth decreased and height growth increased with each succeeding period. The optimum basal area for volume production (both cubic and board-foot measures) was estimated to be 110 ft²/acre. Optimum stocking levels and resulting stand performance are predicted for a common thinning practice.

Retrieval Terms: Pinus ponderosa, Pinus jeffreyi, thinning response, diameter growth, basal area, increment, stocking level, plantations, Modoc National Forest.

Oliver, William W.
1979. **Fifteen-year growth patterns after thinning a ponderosa-Jeffrey pine plantation in northeastern California.** Res. Paper PSW-141, 10 p., illus. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

Growth was analyzed after one thinning in a plantation of pole-size ponderosa and Jeffrey pines on land having a site index of 50 feet at 50 years. Periodic annual increment was determined for each of three 5-year periods. On this basis, increment in diameter and cubic volume were found to be related closely to stand basal area only. Basal area and height increment, however, were also related to time since thinning; basal area growth decreased and height growth increased with each succeeding period. The optimum basal area for volume production (both cubic and board-foot measures) was estimated to be 110 ft²/acre. Optimum stocking levels and resulting stand performance are predicted for a common thinning practice.

Retrieval Terms: Pinus ponderosa, Pinus jeffreyi, thinning response, diameter growth, basal area, increment, stocking level, plantations, Modoc National Forest.

Oliver, William W.
1979. **Fifteen-year growth patterns after thinning a ponderosa-Jeffrey pine plantation in northeastern California.** Res. Paper PSW-141, 10 p., illus. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

Growth was analyzed after one thinning in a plantation of pole-size ponderosa and Jeffrey pines on land having a site index of 50 feet at 50 years. Periodic annual increment was determined for each of three 5-year periods. On this basis, increment in diameter and cubic volume were found to be related closely to stand basal area only. Basal area and height increment, however, were also related to time since thinning; basal area growth decreased and height growth increased with each succeeding period. The optimum basal area for volume production (both cubic and board-foot measures) was estimated to be 110 ft²/acre. Optimum stocking levels and resulting stand performance are predicted for a common thinning practice.

Retrieval Terms: Pinus ponderosa, Pinus jeffreyi, thinning response, diameter growth, basal area, increment, stocking level, plantations, Modoc National Forest.

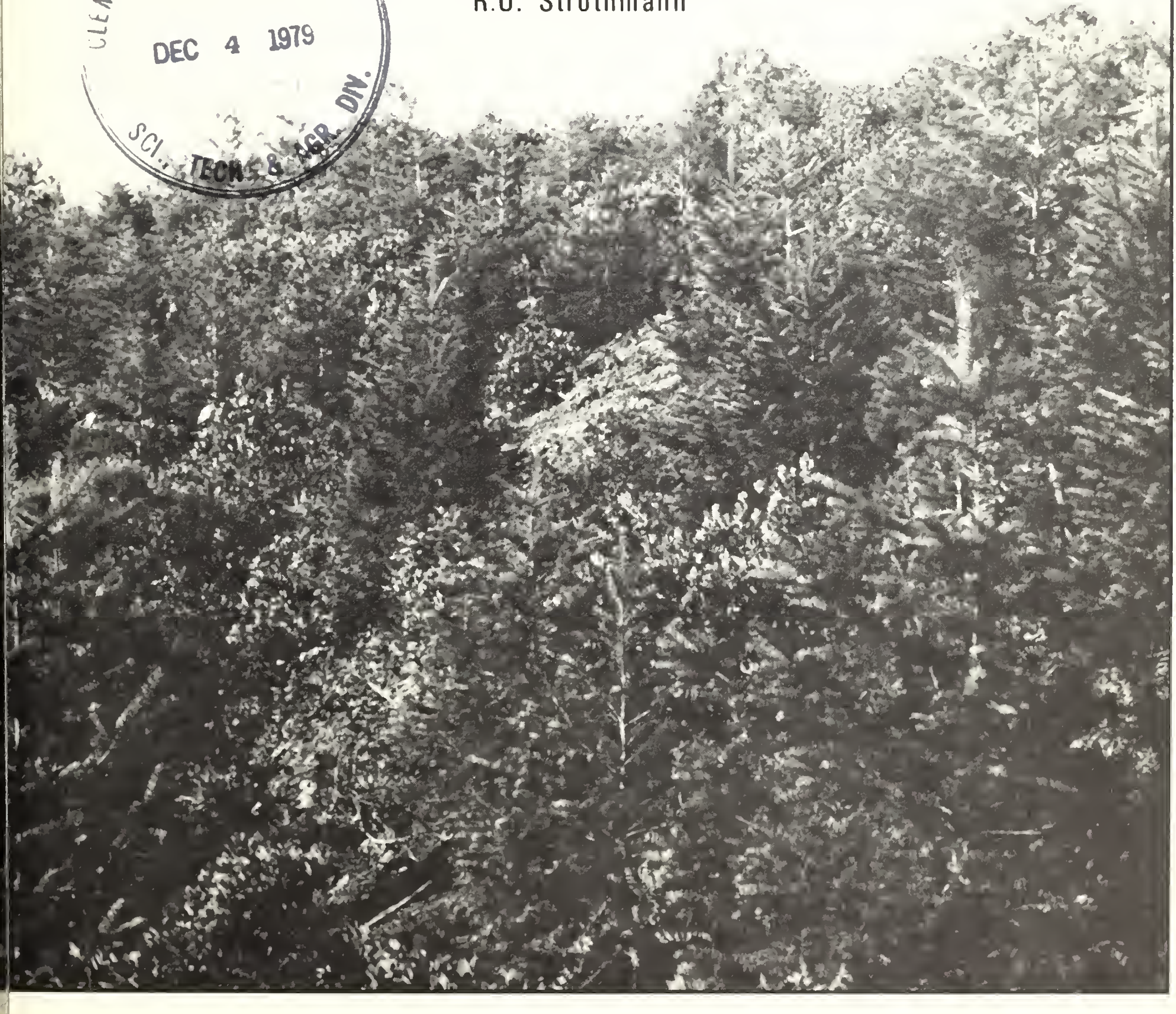
PACIFIC SOUTHWEST
Forest and Range
Experiment Station

ST SERVICE
EPARTMENT OF AGRICULTURE

Regeneration of Douglas-fir cutblocks on the Six Rivers National Forest in northwestern California

CLEMSON UNIVERSITY LIBRARY
DEC 4 1979
SCI., TECH. & AGR. DIV.

R.O. Strothmann



RESEARCH PAPER PSW-142

The Author

R.O. STROTHMANN is doing research on the silviculture of redwood and Douglas-fir forests, with headquarters in Arcata, California. He earned bachelor's (1950), master's (1951), and Ph.D. (1964) degrees in forestry at the University of Michigan, and has been on the Station's staff since 1964.

Acknowledgment

Special thanks are due William G. O'Regan, formerly Station biometrician, and David A. Sharpnack, Station statistician, for their assistance in developing the quadrat sampling scheme and the analysis technique used in this study.

Regeneration of Douglas-fir cutblocks on the Six Rivers National Forest in northwestern California

R.O. Strothmann

CONTENTS

Page

Introduction 1

Study Area 1

Methods 2

Results 2

- Overall Patterns 2
- Individual Factors 4

Discussion 6

- Influence of Ranger District and Site 6
- Age 6
- Cutblock Size and Logging Method 6
- Elevation and Planting Time 7
- Choice of Dependent Variable 7
- Relation of Quadrat Size to Stocking Standards 8

Literature Cited 9

Pacific Southwest Forest and Range Experiment Station
P.O. Box 245
Berkeley, California 94701

May 1979

IN BRIEF . . .

Strothmann, R.O.
1979. **Regeneration of Douglas-fir cutblocks on the Six Rivers National Forest in northwestern California.** Res. Paper PSW-142, 9 p. illus. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

Retrieval Terms: artificial regeneration; planting; plantations; stocking; Six Rivers National Forest; California; Douglas-fir; *Pseudotsuga menziesii*.

A regeneration survey was conducted on 61 cutblocks on three Ranger Districts of the Six Rivers National Forest. The cutblocks were planted during the period from 1964 through 1975. The purpose was not only to ascertain the current stocking status, but also to determine whether certain characteristics of the cutblocks or plantations were associated with either good or poor stocking. A 2-milacre (8.09 m^2) quadrat was used, on the basis that 500 well-spaced trees per acre (1235/ha) would represent full stocking at age 3 to 5 years.

The cutblocks ranged in size from 6 to 68 acres (2.4 to 27.5 ha) and in elevation from 1300 to 4900 feet (396 to 1494 m). On 51 of the 61 cutblocks, Douglas-fir was the species initially planted; on the remaining 10 it was ponderosa pine. One-third of the cutblocks had been replanted, several as many as three times.

Seven species of conifers were found on the surveyed quadrats, not all of them commercially valuable under present market conditions. Douglas-fir was by far the most abundant species present, occurring on more than 77 percent of all stocked quadrats. Ponderosa pine was second, being present on 22 percent of the quadrats classified as stocked. White fir was present on nearly 6 percent. None of the remaining four species—incense-cedar, sugar pine, Port-Orford-cedar, or Pacific yew—occurred on more than 3 percent of the total number of stocked quadrats. Some quadrats had more than one species present.

For the study as a whole, the average stocking was 42.2 percent, and the average number of trees per acre was 396 (979/ha). The best stocking on any cutblock was 81 percent and the poorest, 15 percent; the corresponding trees-per-acre values were 1246 and 81, (3079 and 200/ha), respectively.

Stocking declined among the three Districts in a north-to-south direction as sites became hotter and drier. The most northerly District (Orleans) had an average stocking of 48 percent, while the most southerly (Mad River) averaged only 37 percent.

For the study as a whole, one-fifth of the cutblocks had a stocking of 60 percent or greater, nearly one-third had a stocking of 50 percent or greater, and more than three-quarters had a stocking of 30 percent or greater. Ten percent of the cutblocks had 800 or more trees per acre (1977/ha), nearly 40 percent had 400 or more (988/ha), 54 percent had 300 or more (741/ha), and 77 percent had 200 or more (494/ha).

Advance reproduction constituted only a small part of the total reproduction in the survey, occurring on only 4.3 percent of the stocked quadrats. All seven coniferous species were present as advance reproduction, with Douglas-fir most abundant, and white fir next in this category.

On eleven cutblocks, no stocked quadrats were overtopped by brush. On the remaining 50, the proportion of stocked quadrats overtopped ranged from 1 to 55 percent. On only four cutblocks, however, were more than 30 percent of stocked quadrats overtopped by brush or hardwoods.

To evaluate the influence of various individual factors on regeneration success, a backwards step-wise regression technique was used, based on data from 36 of the 61 cutblocks. The final model had an R^2 of 0.9136.

For the 36-cutblock sample, statistical analyses indicated that (1) the most favorable aspect for regeneration was about 12° east of north, and conversely, the least favorable about 12° west of south; (2) within the range of plantation ages sampled (1 to 12 years), stocking improved as age increased, probably because of the continuing establishment of natural seedlings among the planted trees; (3) stocking decreased as cutblock size increased; (4) stocking was best on the best sites; (5) cutblocks which were tractor-logged had better stocking than those which were cable-logged; (6) stocking was better at elevations below 3000 feet (914 m) than at higher elevations; and (7) cutblocks planted in December, January, or May were better stocked than those planted in other months.

If the Forest Service's minimum satisfactory stocking standard of "100 thrifty well-scattered trees per acre that are free to grow and have completed one growing season" is applied, only 2 of the 61 cutblocks could be called regeneration failures on the basis of number of trees. Some others, however, would fail to meet the specification that the trees be well scattered.

Prompt and successful regeneration of cutover forest land is a major concern of forest land owners. Prompt regeneration reduces rotation length, minimizes the period of susceptibility to accelerated erosion, and shortens the period of unsightliness that follows logging.

The adverse site or climatic characteristics of some areas challenge the regeneration specialist. Hot, dry summers, steep topography, and unstable soils all increase the difficulty of establishing regeneration after logging. These problems exist on many areas of the Six Rivers National Forest in northwestern California.

In assessing regeneration efforts on some of the cutblocks planted since 1964 on three Ranger Districts on this Forest, my intent was not only to inventory stocking, but also to find out whether regeneration success (or failure) could be associated with particular site characteristics, or with such variables as method of logging, size of cutblock, and years since planting. This paper reports data on percent stocking and numbers of trees per acre for more than 60 cutblocks, and also the results of a regression analysis of a smaller sample of 36 cutblocks to evaluate the influence of specific factors on percent stocking.

STUDY AREA

The Six Rivers National Forest, in extreme northwestern California, is within 6 miles (9.7 km) of the Pacific Ocean near its northern boundary, but nearly 35 miles (56.3 km) from the coast near its southern boundary. It is long and narrow, extending about 140 miles (225 km) in a north-south direction, but generally less than 20 miles (32 km) in an east-west direction.

The topography for the most part is steep and rugged, with elevations exceeding 6000 feet (1829 m) in a few areas. Soil development is influenced by climatic variation and by topographic variations in both the metamorphic and sedimentary rock types commonly occurring on the Forest (Zinke and Colwell 1965). A topographic sequence on schist rock, for example, shows a progression of increasing development from valley bottom to ridgetop, traversing soils in the Sheetiron, Masterson, Orick, and Sites soil series. This sequence illustrates that the most developed soil on this rock type is often found on plateau-like ridge tops, and always on apparently older surfaces.

The reverse pattern also occurs, however, and is the more common sequence found in California mountain forests (Zinke and Colwell 1965). On graywacke sandstone, for example, an elevational transect begins with the better developed Josephine soil series at the lower elevations, then progresses with increasing elevation through the lesser developed Hugo soil series, and finally reaches the least developed Hoover series.

Throughout most of the area included in this study, Douglas-fir *(Pseudotsuga menziesii* [Mirb.] Franco var. *menziesii)* is the predominant tree species. Although it occurs in pure or nearly pure stands in some localities, it is commonly associated with several other species. Chief associates are ponderosa pine *(Pinus ponderosa* Laws.), sugar pine *(P. lambertiana* Dougl.), incense-cedar *(Libocedrus decurrens* Torr.), Port-Orford-cedar *(Chamaecyparis lawsoniana* [A. Murr.] Parl.), white fir *(Abies concolor* [Gord. & Glend.] Lindl.), Pacific madrone *(Arbutus menziesii* Pursh), tanoak *(Lithocarpus densiflorus* [Hook & Arn.] Rehd.), and several true oaks *(Quercus* spp.).

Three forest cover types (Soc. Amer. For. 1975) are probably represented, namely, Pacific Douglas-fir (type 229), Pacific ponderosa pine—Douglas-fir (type 244), and Ponderosa pine—sugar pine—fir (type 243). In limited areas, Port-Orford-cedar—Douglas-fir (type 231) may also be present.

METHODS

Time permitted examination of 61 cutblocks, or approximately 20 on each of the three selected Ranger Districts (Orleans, Lower Trinity, and Mad River). In addition to good geographic distribution of our sample, a reasonably good distribution over the full range of plantation ages (1-12 years) was desirable. Therefore one-third of the sample of cutblocks was taken from those which were planted 1 to 4 years ago, another third, 5 to 8 years ago, and a final third, 9 to 12 years ago. Within these constraints, the sample was randomly chosen from the population of cutblocks planted since 1964 on the three Districts, except for cutblocks for which good records were not available.

For each selected cutblock, certain basic data were taken from the District records: size of cutblock, year of cutting, logging method, month and year of planting, species planted, seed source, dates of any replanting, cutblock elevation, and Douglas-fir site class (as defined by McArdle and others 1961). Aspect and slope were determined in the field.

The selected cutblocks ranged in size from 6 to 68 acres (2.43 to 27.52 ha), and in elevation from 1300 to 4900 feet (396 to 1494 m). On 51 of the 61 cutblocks, Douglas-fir was the species initially planted; on the remaining 10 it was ponderosa pine. One-third (21) of the blocks had been replanted—some of them more than once (12 once, 5 twice, and 4 three times). Douglas-fir and ponderosa pine were used about equally in the replanting (Douglas-fir on 10 cutblocks and ponderosa pine on 11).

Because the Six Rivers National Forest normally plants about 400 to 500 trees per acre (988 to 1235/ha), I chose a quadrat size of 2 milacres (8.09 m^2) as most appropriate, since there would be 500 such quadrats per acre (1235/ha). This choice assumes that 500 well-spaced young conifers per acre represents full stocking—an assumption I considered reasonable for the early establishment phase.

The sampling method was a modification of the two-stage sampling technique described by Cochran (1963). Briefly outlined, the procedure for each cutblock was as follows: (1) establish a convenient base line through the cutblock; (2) divide the block into four approximately equal parts along this base line; (3) randomly select the locations of two sampling lines (at right angles to the base line) within each quarter; (4) determine the total number of quadrats needed on the cutblock to achieve a sampling intensity of four quadrats per acre (9.88/ha); (5) calculate the spacing needed between quadrats along the sampling lines to attain the desired sampling intensity; and (6) randomly select a starting point for the set of quadrats along each of the eight sampling lines.

A quadrat was considered stocked if it had at least one live, healthy conifer 1 foot (0.305 m) tall or taller. Height of the tallest conifer on each quadrat was measured to the nearest foot. Field crews also recorded its species, and whether it was of prelogging or postlogging origin. Other information recorded for each quadrat was the total number of live conifers present, by species, and whether or not the tallest conifer was overtopped by brush or hardwoods.

Data were analyzed by regression techniques to evaluate the influence of various site and other factors on percent stocking. The final model was selected using the backwards stepwise procedure described by Draper and Smith (1966).

RESULTS

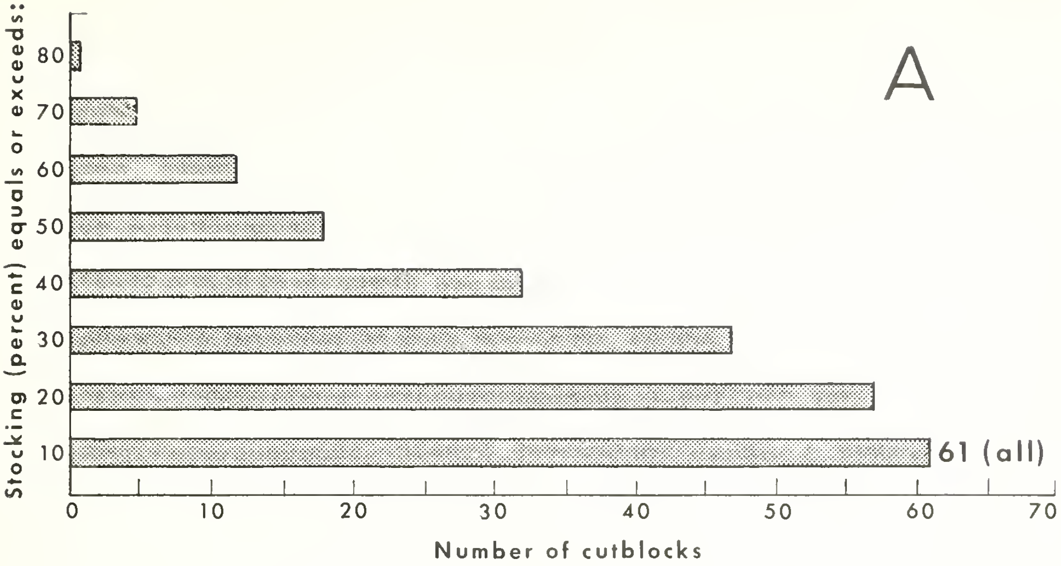
Overall Patterns

During the survey 6032 2-milacre quadrats were examined. For the study as a whole, the average stocking (trees 1 foot or taller) was 42.2 percent, and the average total number of trees per acre was 396 (979/ha).

The heaviest stocking encountered on any cutblock was 81 percent, found in an 11-year-old plantation on a 24-acre (9.71-ha) northeast-facing cutblock on site class 2. The poorest stocking encountered was 15 percent, found in a 4-year-old plantation on a 26-acre (10.52-ha) west-facing cutblock on site class 4. The trees-per-acre figures for these cutblocks were 1246 and 81, (3079 and 200/ha), respectively. Although the Forest does have plantations which fall outside of these extremes (a few plantations reportedly have in excess of 1500 trees per acre, 3705/ha), our sample covered the normal range quite well.

Average stocking by Ranger District revealed an interesting pattern, as follows: Orleans—47.96 percent, Lower Trinity—40.31 percent, Mad River—36.91 percent (see Discussion).

The number of cutblocks on which the percent stocking exceeds specific thresholds is shown in *figure 1A*. Only one cutblock exceeded 80 percent; 18, however, exceeded 50 percent; more than half exceeded 40 percent; and more than three-quarters exceeded 30 percent.



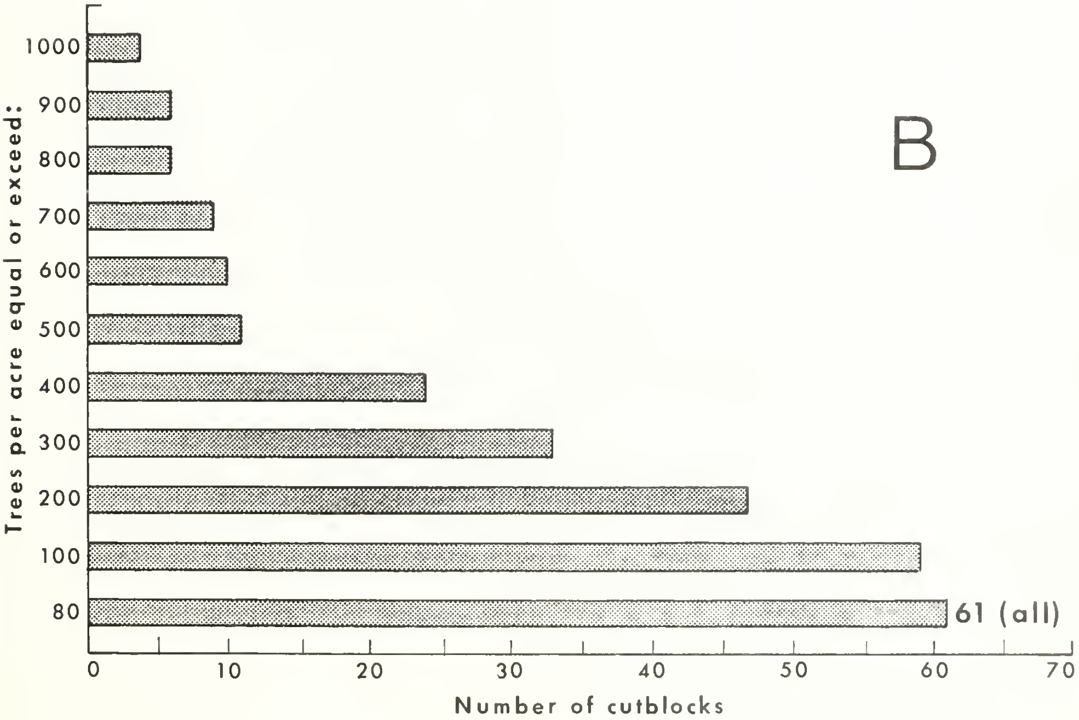


Figure 1—Patterns of stocking are shown as (*A*) number of cutblocks on which percent of quadrats stocked equals or exceeds specific thresholds, and (*B*) number of cutblocks on which the total number of trees per acre equals or exceeds specific thresholds. Data are based on trees at least 1 foot tall.

The number of cutblocks on which the number of trees per acre exceeds specific thresholds is shown in *figure 1B*. Four cutblocks had more than 1000 trees per acre (2471/ha), 10 at least 600 trees per acre (1483/ha), 33 (about 54 percent), at least 300 trees per acre (741/ha), and 47 (77 percent) at least 200 trees per acre (494/ha).

During the course of the survey, seven species of conifers were encountered, some only infrequently. Not all are commercially valuable under present market conditions, but because marketability standards change, all were included as countable stocking if they met the minimum size requirement (at least 1 ft tall). The relative importance of the seven species, as shown by the percentage of all stocked quadrats on which they were present, and the percentage of stocked quadrats on which they were the tallest conifer, is as follows:

	Present	Tallest
	Percent	
Species:		
Douglas-fir	77.1	73.6
Ponderosa pine	22.1	19.8
White fir	5.8	4.2
Incense-cedar	2.7	1.4
Sugar pine	1.2	0.7
Pacific yew	0.2	0.2
Port-Orford-cedar	0.1	0.1
	(109.2)[1]	100.0

White fir was present chiefly on cutblocks at the higher elevations, and Pacific yew (*Taxus brevifolia* Nutt.) and Port-Orford-cedar occurred on only five quadrats and three quadrats, respectively. All seedlings of the four least abundant species were of natural origin.

The tabulation shows that the species pattern for the tallest conifer on each quadrat is much the same as for the frequency of occurrence. On almost 94 percent of all sampled quadrats that were stocked with one or more conifers, the dominant conifer was either a Douglas-fir or a ponderosa pine.

Advance reproduction constituted only a small part of the total, occurring on only 4.3 percent of the stocked quadrats. Douglas-fir was the most abundant species among the advance reproduction, closely followed by white fir. The others, in declining order of occurrence, were ponderosa pine, incense-cedar, sugar pine, Port-Orford-cedar, and Pacific yew.

Overtopping of conifers by brush or hardwoods was not a problem on 11 of the 61 cutblocks, as none of their stocked quadrats were classified as overtopped. On the remaining 50, the proportion of stocked quadrats which was overtopped ranged from 1 to 55 percent. On only 14 cutblocks, however, were more than 20 percent of stocked quadrats overtopped, and on only 4 was the percentage above 30.

Individual Factors

The influence of individual factors on percent stocking could be summarized as stocking averages for the subclasses of each factor. These would be of limited value, however, and could even be misleading. For this reason, results are best presented in a regression model.

Many preliminary models were tested before the final model was developed. Two topographic variables—aspect and percent slope—were handled jointly because, in various combinations, one can either reinforce or counteract the effect of the other. The approach adopted was suggested by Stage (1976) and is designed to deal with this problem. Stage recommends that "the variables to represent the combined effect of slope and aspect be defined as the tangent of slope (slope percent) times the sine and cosine, respectively, of the azimuth. In this way, plots on flat ground will have a zero value for these two variables, but plots on steep ground will have high weights for the sine and cosine of aspect." Stage's method also identifies the most favorable and least favorable azimuths.

In the preliminary regression models tested, site class was found to be a highly important variable in accounting for stocking differences. Unfortunately, site information was available on only two of the three Ranger Districts studied. Hence, the final regression model was developed using data from 36 cutblocks on these two Districts.

Replanting history was not included as a variable in the model because only 9 of the 36 cutblocks had been replanted. Limiting the model to the 27 cutblocks which had not been replanted would have further reduced the data base. Since a preliminary analysis revealed that the replanted cutblocks were still among the most poorly stocked of the 36-cutblock sample, they were allowed to remain in the model.

Seed source was also excluded as a variable because this information was unavailable for many of the cutblocks, and, on some cutblocks, trees from more than one source had been planted.

The final regression model is as follows:

$Y = f$ (District, $\sin\alpha \tan s$, $\cos\alpha \tan s$, elevation, age, logging method, site, month planted, cutblock size) where

---

[1] More than one species found on some quadrats.

Y = stocking (percent of 2-milacre quadrats stocked with a conifer seedling at least 1 foot tall, either planted or natural)
α = azimuth (degrees measured clockwise from north)
s = slope percent

For this model, $R^2 = 0.9136$

All variables were handled as class variables except plantation age, cutblock size, and the transformed values for slope and aspect, which were handled as continuous variables. In preliminary trials, elevation yielded slightly better results (higher R^2) when treated as a class variable than as a continuous variable; hence it was handled as a class variable in the final regression model.

The analysis revealed that for the cutblocks included in the sample, the most favorable aspect with respect to stocking percent was 11°37′ east of north; conversely, the least favorable was 11°37′ west of south.

The effects of the individual variables in the model are shown by the regression coefficients listed in *table 1*. The reader is cautioned that some of these model "effects" are not fully in agreement with known biological patterns. The probable explanations for this are given in the Discussion.

Table 1—*Variables which exert a significant influence on the percent stocking of 36 cutblocks on two Ranger Districts of the Six Rivers National Forest, California.*

Variable group and/or specific variable	Regression coefficient	Frequency
District:		
Orleans	13.9696	18
Lower Trinity	-13.9696	18
Aspect/slope:		
sin ∝ tan s	2.6590	36
cos ∝ tan s	12.9398	36
Elevation (ft):		
0-2000	7.3063	3
2001-3000	8.0847	12
3001-4000	-4.0001	15
4001-5000	-9.8223	6
Age	2.7399	36
Logging method:		
Tractor	9.7979	11
Cable	-4.3111	25
Site class:		
2	25.7125	7
3	-4.9652	20
4	-8.9648	9
Month planted:		
November	-2.4510	4
December	10.9757	5
January	8.9089	1
February	-7.0212	3
March	-9.1768	10
April	-1.5624	8
May	14.2695	5
Cutblock size	-0.5367	36
Intercept	38.7272	

An examination of the regression coefficients reveals (as noted earlier) that (1) cutblocks on the Orleans Ranger District are better stocked than those on the Lower Trinity District; (2) the positive coefficient for age (2.7399) indicates that as age increases (within the limits of the ages sampled), stocking also tends to increase; (3) the negative coefficient for cutblock size (-0.5367) indicates that stocking tends to decrease somewhat with increasing cutblock size; and (4) the range in coefficients for site class emphasizes the influence of this factor on regeneration success.

Other conclusions are that, in our sample of cutblocks, tractor logging had a more favorable influence on subsequent stocking than did cable logging (regression coefficient of 9.7979 vs. -4.3111). Also, stocking tends to be greater at elevations below 3000 feet (914 m) than at higher elevations.

For month of planting, the coefficients indicate that better stocking has occurred on cutblocks planted in December, January, and May than on cutblocks planted in November, February, March, or April.

Table 1 can be used to predict percent stocking for cutblocks on the two Ranger Districts for which the model is applicable. The coefficients for the appropriate specific variables are simply added (once the coefficients have been multiplied by the value of the variable). *Table 2* is an example.

Table 2—*Example of how the regression coefficients from table 1 can be used to predict percent stocking.* [1]

Variable	Multiplier for value of continuous variables	Regression coefficient	Entry for summation
District: Lower Trinity		-13.9696	-13.9696
Aspect: East (90° azim.)			
Slope: 63 percent			
sin 90 tan 63 =	1.9626	2.6590	5.2186
cos 90 tan 63 =	0.0000	12.9398	0.0000
Elev.: 2500 feet (2001-3000)		8.0847	8.0847
Age: 8 years	8	2.7399	21.9192
Logging method: cable		-4.3111	-4.3111
Site class: 4		-8.9648	-8.9648
Month planted: March		-9.1768	-9.1768
Cutblock size: 8 acres	8	-0.5367	-4.2936
Intercept		38.7272	38.7272
Predicted percent stocked			33.2338
Actual percent stocked (from survey)			32.40

---

[1] Data from cutblock 3. Predictions are valid only for the two Ranger Districts from which data for the regression model were obtained.

DISCUSSION

Many of the findings of this study conform to expectations, and can be accounted for by well-established biological relationships. Other findings seem to contradict these known patterns of relationships. Some possible explanations for the regeneration patterns encountered are presented here.

Influence of Ranger District and Site

The average stocking by Ranger District showed a definite pattern of decline from the most northerly to the most southerly of these three Districts. This is not surprising since sites become hotter and drier—and consequently less favorable for Douglas-fir—as one moves southward within the Six Rivers National Forest. Vegetation patterns are a clue—oak types increasingly intermingle with grassy glades as one reaches the Mad River (most southerly) Ranger District. Forest personnel recognize these adverse conditions and are currently doing less clearcutting and more shelterwood cutting on the Mad River District.

The importance of site quality in influencing regeneration success was noted earlier. This is not to say that the best sites are necessarily the easiest to regenerate. The very conditions (good soil depth, texture, moisture, and nutrient status) which favor conifer seedling establishment also favor the establishment and growth of competing vegetation. Also, animal damage is sometimes more severe on good sites than on poor ones. Nevertheless, if there is thorough site preparation followed by prompt planting and timely release, the best stocking can logically be expected to be associated with the best sites.

Age

The pattern of increased stocking with increased age of plantation is most likely due to the establishment of natural seedlings among the planted trees. In our survey we made no attempt to distinguish between planted and natural seedlings, and, indeed, such a distinction would not always be easy to make in the older plantations. That naturals do "seed in" among planted trees is, however, a well-established fact, as evidenced by numerous plantations where ponderosa pine was the only species planted, but where a prominent Douglas-fir component later appeared. We noticed this mixture on 7 of the 10 cutblocks in our survey which had been planted initially with pine.

Although mortality obviously does occur in plantations, and sometimes even results in a regeneration failure, there nevertheless appears to be a definite countertrend with age in many plantations. Early mortality is frequently offset by the subsequent establishment of new trees through natural seeding.

The possibility was also examined that the pattern of better stocking in the older plantations might be partly due to greater precipitation in the growing season (April through September) during the year of establishment. Although this possibility cannot be ruled out entirely, the pattern of wet and dry years is quite erratic. There is no definite trend to suggest that the older plantations were favored with greater growing-season precipitation than were the more recent ones. For example, the growing season of 1964 (the earliest year included in our study) was the fourth driest, 1965 was the third wettest, and 1966 was the second driest of the 12 years in the study.

Cutblock Size and Logging Method

The finding that stocking tends to decrease as cutblock size increases is a pattern which others also have noted (Worthington, 1953; Roy, 1960). Proximity to a seed source is certainly one explanation for this. Large portions of the larger cutblocks are beyond the range of normal seed dispersal from the surrounding forest. Also, especially on south and west aspects, the microclimate following clearcutting on large cutblocks is sometimes harsh and unfavorable for the survival of young conifers, either planted or natural. If thorough site preparation precedes careful planting with good stock, however, and competing vegetation is kept under control, good survival of planted Douglas-fir is possible on harsh sites (Strothmann, 1972, 1976).

Logging method apparently affected regeneration success for several reasons. Tractor logging and the associated piling and burning of slash normally exposes more mineral soil than does cable logging and broadcast burning. Therefore, tractor logging provides a greater proportion of favorable seedbed on which natural regeneration can become established. Also, tractor-logged areas may be somewhat easier to plant because they have fewer obstructions for the planting crew and are on gentler slopes than cable-logged areas. And, because of the gentler slopes, the soils may sometimes be deeper.

Elevation and Planting Time

It is not clear why stocking was better on cutblocks below an elevation of 3000 feet (914 m) than on cutblocks at higher elevations. Perhaps the most likely explanation is that the timing of planting is often more critical at higher elevations. There is a relatively short period when planting conditions are favorable, and consequently when reasonable success can be expected.

On the one hand, planting may have been done too early on some of the higher elevation cutblocks. Even though the ground may not have been frozen, soil temperatures may have been too low for prompt seedling root growth. Under such circumstances, the seedlings are vulnerable to desiccation by sun and wind because their root systems are still relatively inactive and thus unable to replace seedling moisture losses adequately.

On the other hand, planting may sometimes have been done too late, as when a cutblock is free of snow and otherwise in good planting condition, but portions of the access road are still snow-blocked. When the road finally becomes driveable, the soil at the planting site may already be too dry for optimum planting success.

Another reason for the poorer average stocking on the higher elevation cutblocks could be gopher activity, which is generally more common at higher elevations.

The variable "month of planting" showed an expected relationship to stocking in some instances, but an unexpected relationship in others. The negative regression coefficient for November, and the positive coefficients for December and January *(table 1)* conform to normal experience. November is often regarded as too early to plant, but December and January are generally considered to be good planting months. February is also generally thought to be a good month to plant, but in this survey it was characterized by a large negative regression coefficient, as was March. May had a very high positive coefficient, suggesting it is an excellent month to plant.

Possible explanations for these seemingly anomalous patterns include sample size, soil moisture and temperature, and the physiological condition of the planting stock. Sample size was obviously smaller than desirable for some elements of this variable, and any untypical cutblocks which may have been included within the small sample for a particular month could have distorted the normal pattern.

Deficiencies in soil moisture and soil temperature could also influence the month-of-planting responses which we encountered. We had no information on the status of these at the time of planting, but both can have an important effect on regeneration success.

Perhaps of even greater importance is the physiological condition of the planting stock, particularly its root growth capacity. Even though soil moisture and temperature may be favorable for seedling growth, a plantation may fail if the seedlings are not in the proper physiological condition when they are planted. This is largely determined by their physiological condition at the time of lifting (Stone and others 1962), and by temperatures maintained during storage.

Administrative studies currently underway at the Forest Service's Humboldt Nursery at McKinleyville, California, show that there is considerable variation in root growth capacity and field survival of Douglas-fir, depending upon seed source and lifting date (Jenkinson and Nelson 1978). Some sources can be lifted and stored anytime during the 4 months between early November and early March and outplanted with first-year survival potentials ranging from 88 to 98 percent. Other sources have a much narrower "lifting window," in some cases covering only about a 6-week period centered around early February as the optimum lifting time.

Some unexplained failures in earlier regeneration efforts were undoubtedly due to lack of awareness of the importance of lifting and storage date as influenced by seed source. As previously mentioned, seed source information in this study was too limited to be of value, and hence was not used in the analysis.

In addition to not having information on soil moisture, soil temperature, and seedling physiological condition at time of planting, we also lacked information on weather conditions during planting, on how carefully the stock was handled, and on the overall quality of the planting job itself. The unknown impacts of these and other factors in our study are doubtless responsible for some of the apparent anomalies.

Choice of Dependent Variable

Some inconsistencies might be resolved if a "cleaner" dependent variable were used—that is, percent survival of the number of trees actually planted, rather than percent stocking of an assumed standard. If, for example, 270 uniformly spaced trees per acre were found at the time of the survey, this would represent 54 percent stocking, using the 500-tree-per-acre standard; the cutblock might be considered somewhat understocked. However, if only 300 trees per acre had been originally planted on this cutblock, the presence of 270 per acre (assuming none were "naturals") would represent a 90 percent survival rate. Viewed from this standpoint, the regeneration effort would be considered quite successful.

Obviously, the number of trees per acre which were originally planted is a valuable item of information for interpreting regeneration success. Unfortunately, this information was available for fewer than half of the cutblocks; hence, the cruder yardstick for evaluating regeneration success was used.

Relation of Quadrat Size to Stocking Standards

Because experience with 2-milacre quadrats is limited, no general guidelines exist as to what percentage of them might constitute satisfactory stocking. Stein (1978) states that there is also no current consensus on the percent of stocked 1- or 4-milacre plots required to constitute satisfactory stocking, although in the past, 65 to 70 percent stocking of 4-milacre plots, or 30 to 40 percent of 1-milacre plots was considered satisfactory.

My choice of a 2-milacre quadrat implies a stocking standard of 500 well-spaced trees per acre (1235/ha), but this does not mean that 500 trees per acre are desired at rotation age. As Stein (1978) points out, full stocking need not be tied to yield table data, nor to number of trees at rotation age. It can as readily be based on the maximum number of trees desired before the first commercial thinning, or it could simply be the number of well-distributed trees required per acre at the end of the reforestation period.

In this study I considered 500 well-spaced trees per acre to be a stocking goal which might be desirable about 3 to 5 years after planting. This would assure relatively early control of the site by the desired tree species, thereby reducing the chances of a take-over by brush, grass, or other types of vegetation.

How do the cutblocks examined in this study measure up when compared with several prescribed stocking standards for northern California? Personnel of the Six Rivers National Forest indicate that they would like to have at least 300 well-established trees per acre (741/ha) on their cutblocks, but they will accept fewer. The Forest Service Manual[2] states that "Minimum satisfactory stocking of a planted area is 100 thrifty well-scattered trees per acre (247/ha) that are free to grow and have completed one growing season. These can be natural seedlings of acceptable species for the site. Acceptable trees do not need to fit the original spacing pattern."

The California Forest Practices Act, although not applicable to federally-owned lands, is nevertheless of interest here. It defines minimum acceptable stocking as 300 trees per acre within 5 years after completion of harvesting operations. The 300-tree standard can be met by various combinations of tree sizes. If all trees on the area are less than 4 inches in diameter, the full count of 300 is required; this number is reduced if larger trees are present.

If we use the 100-trees-per-acre Forest Service guide as the minimum acceptable stocking, only two cutblocks in our survey failed to meet this standard. However, some of the other cutblocks would fall short of the specification that the trees be well scattered.

If we use 300 trees-per-acre as the minimum acceptable stocking, only 54 percent of the surveyed cutblocks were adequately stocked *(fig. 1B)*. An additional 23 percent, however, had at least 200 trees per acre (494/ha), and might be considered as having marginally adequate stocking if subsequent mortality is low.

Although this study has identified numerous variables as having favorable or unfavorable influences on stocking, not all can be altered by the regeneration specialist. He cannot, for example, change the aspect of a cutblock from south to north, or change its elevation, or appreciably change its site quality. However, if he knows which of these variables tend to be associated with poor stocking, he can compensate for this by planting more trees per acre.

Other variables, such as logging method and cutblock size, are under the forest manager's control, although also influenced by topographic, economic, and environmental constraints. Within these constraints, the forest manager can improve his chances for regeneration success by keeping the size of clearcut blocks as small as feasible, and by doing a good job of site preparation.

---

[2] Forest Service, U.S. Department of Agriculture. 1965. Forest Service Manual 2472.b (Seeding and Planting). R-5 Supp. 57.

LITERATURE CITED

Cochran, W.G.

1963. **Sampling techniques.** 2nd ed., 413 p. Wiley, New York.

Draper, N.R., and H. Smith

1966. **Applied regression analysis.** 407 p. Wiley, New York.

Jenkinson, James L., and James A. Nelson

1978. **Seed source lifting windows for Douglas-fir in the Humboldt Nursery.** *In* Proc. Western Forest Nursery Conf. [Eureka, Calif. Aug. 7-9, 1978], p. B-77 to B-95.

McArdle, Richard E., Walter H. Meyer, and Donald Bruce

1961. **The yield of Douglas-fir in the Pacific Northwest.** U.S. Dep. Agric. Tech. Bull. 201, 74 p.

Roy, Douglass F.

1960. **Douglas-fir seed dispersal in northwestern California.** U.S. Forest Serv. Pacific Southwest Forest and Range Exp. Stn. Tech. Paper 49, 22 p. Berkeley, Calif.

Society of American Foresters

1975. **Forest cover types of North America (exclusive of Mexico),** 67 p. Soc. Amer. For., Bethesda, Md.

Stage, A.R.

1976. **An expression for the effect of aspect, slope, and habitat type on tree growth.** Forest Sci. 22:457-460.

Stein, William I.

1978. **Reforestation evaluation.** *In* Regenerating Oregon's forests, Brian D. Cleary, Robert D. Greaves, and Richard K. Hermann, eds. 287 p. Oreg. State Univ. Ext. Serv., Corvallis.

Stone, Edward C., James L. Jenkinson, and Stanley L. Krugman

1962. **Root-regenerating potential of Douglas-fir seedlings lifted at different times of the year.** Forest Sci. 8:288-297.

Strothmann, R.O.

1976. **Douglas-fir seedlings planted by four methods . . . results after 10 years.** USDA Forest Serv. Res. Note PSW-310, 4 p. Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif.

Strothmann, Rudolph O.

1972. **Douglas-fir in northern California: effects of shade on germination, survival, and growth.** USDA Forest Serv. Res. Paper PSW-84, 10 p. Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif.

Worthington, Norman P.

1953. **Reproduction following small group cuttings in virgin Douglas-fir.** U.S. Forest Serv. Pacific Northwest Forest and Range Exp. Stn. Res. Note 84, 5 p. Portland, Oregon.

Zinke, Paul J., and W.L. Colwell, Jr.

1965. **Some general relationships among California forest soils.** *In* Forest-soil relationships in North America, proceedings, 2d North American Forest Soils Conf. [Corvallis, Oreg. 1963], p. 353-365.

The Forest Service of the U.S. Department of Agriculture

. . . Conducts forest and range research at more than 75 locations from Puerto Rico to Alaska and Hawaii.

. . . Participates with all State forestry agencies in cooperative programs to protect and improve the Nation's 395 million acres of State, local, and private forest lands.

. . . Manages and protects the 187-million-acre National Forest System for sustained yield of its many products and services.

The Pacific Southwest Forest and Range Experiment Station
represents the research branch of the Forest Service in California and Hawaii.

CLEMSON UNIVERSITY LIBRARY
DOCUMENTS DEPT.

Strothmann, R.O.
1979. **Regeneration of Douglas-fir cutblocks on the Six Rivers National Forest in northwestern California.** Res. Paper PSW-142, 9 p. illus. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

A survey of 61 cutblocks planted since 1964 evaluated stocking of conifers (trees 1 foot tall or taller) on 2-milacre quadrats. Overall stocking percentage averaged 42.2 and ranged from 15 to 81. Overall number of trees per acre averaged 396. In the regression model, based on 36 cutblocks, better stocking was associated with high site class, northerly aspect, elevation below 3000 feet, and tractor (rather than cable) logging. Stocking tended to increase with increasing age of plantation, but decreased with increasing size of cutblocks.

Retrieval Terms: artificial regeneration; planting; plantations; stocking; Six Rivers National Forest; California; Douglas-fir; *Pseudotsuga menziesii.*

Strothmann, R.O.
1979. **Regeneration of Douglas-fir cutblocks on the Six Rivers National Forest in northwestern California.** Res. Paper PSW-142, 9 p. illus. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

A survey of 61 cutblocks planted since 1964 evaluated stocking of conifers (trees 1 foot tall or taller) on 2-milacre quadrats. Overall stocking percentage averaged 42.2 and ranged from 15 to 81. Overall number of trees per acre averaged 396. In the regression model, based on 36 cutblocks, better stocking was associated with high site class, northerly aspect, elevation below 3000 feet, and tractor (rather than cable) logging. Stocking tended to increase with increasing age of plantation, but decreased with increasing size of cutblocks.

Retrieval Terms: artificial regeneration; planting; plantations; stocking; Six Rivers National Forest; California; Douglas-fir; *Pseudotsuga menziesii.*

Strothmann, R.O.
1979. **Regeneration of Douglas-fir cutblocks on the Six Rivers National Forest in northwestern California.** Res. Paper PSW-142, 9 p. illus. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

A survey of 61 cutblocks planted since 1964 evaluated stocking of conifers (trees 1 foot tall or taller) on 2-milacre quadrats. Overall stocking percentage averaged 42.2 and ranged from 15 to 81. Overall number of trees per acre averaged 396. In the regression model, based on 36 cutblocks, better stocking was associated with high site class, northerly aspect, elevation below 3000 feet, and tractor (rather than cable) logging. Stocking tended to increase with increasing age of plantation, but decreased with increasing size of cutblocks.

Retrieval Terms: artificial regeneration; planting; plantations; stocking; Six Rivers National Forest; California; Douglas-fir; *Pseudotsuga menziesii.*

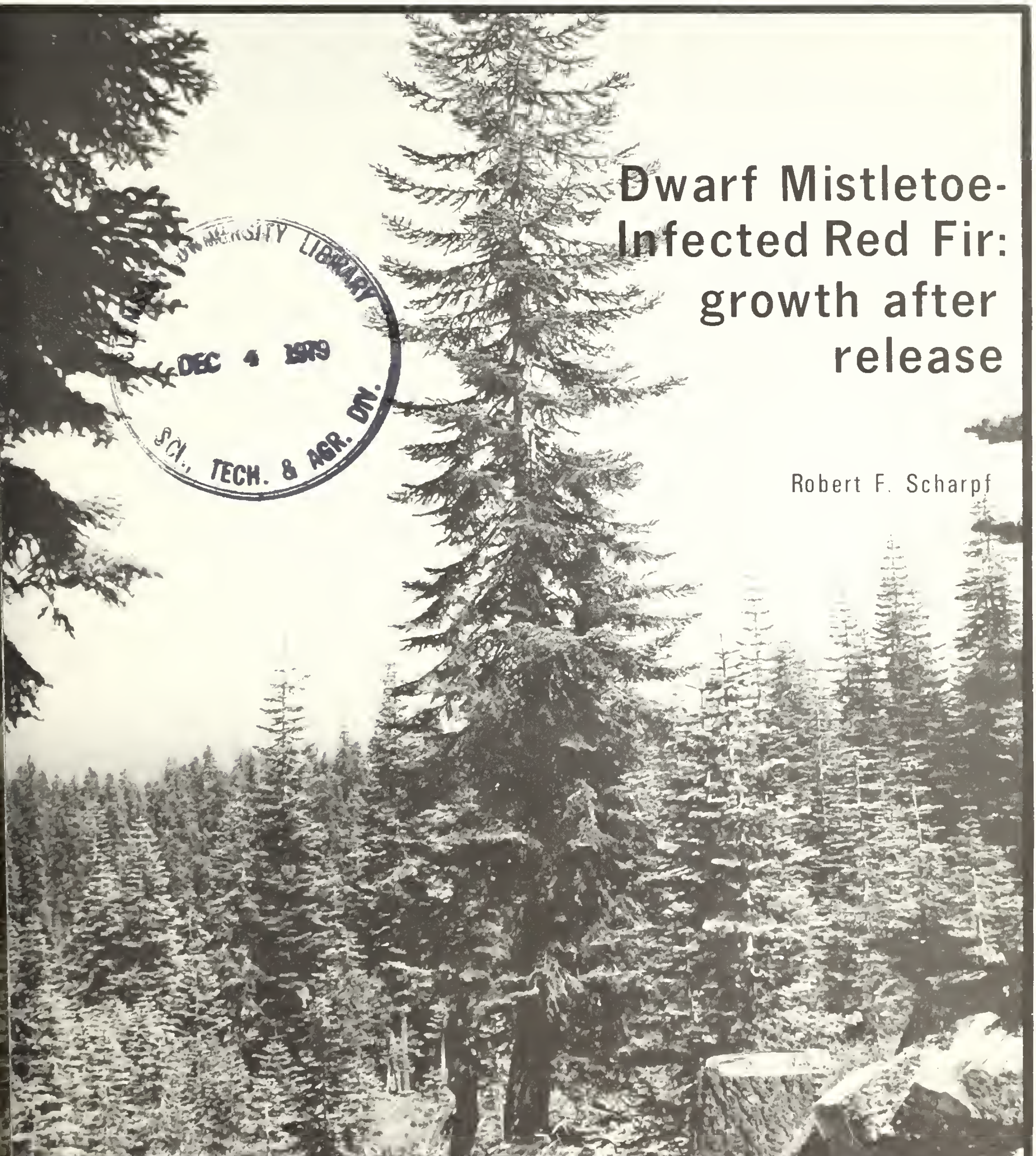
Strothmann, R.O.
1979. **Regeneration of Douglas-fir cutblocks on the Six Rivers National Forest in northwestern California.** Res. Paper PSW-142, 9 p. illus. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

A survey of 61 cutblocks planted since 1964 evaluated stocking of conifers (trees 1 foot tall or taller) on 2-milacre quadrats. Overall stocking percentage averaged 42.2 and ranged from 15 to 81. Overall number of trees per acre averaged 396. In the regression model, based on 36 cutblocks, better stocking was associated with high site class, northerly aspect, elevation below 3000 feet, and tractor (rather than cable) logging. Stocking tended to increase with increasing age of plantation, but decreased with increasing size of cutblocks.

Retrieval Terms: artificial regeneration; planting; plantations; stocking; Six Rivers National Forest; California; Douglas-fir; *Pseudotsuga menziesii.*

PACIFIC SOUTHWEST
Forest and Range
Experiment Station

EST SERVICE
DEPARTMENT OF AGRICULTURE



Dwarf Mistletoe-Infected Red Fir: growth after release

Robert F. Scharpf

UNIVERSITY LIBRARY
DEC 4 1979
SCI., TECH. & AGR. DIV.

RESEARCH PAPER PSW-143

The Author

ROBERT F. SCHARPF, a plant pathologist, is studying problems in forest diseases and their control, with headquarters in Berkeley, Calif. He earned a forestry degree (1954) at the University of Missouri, a master's degree in forestry (1957) and a doctorate in plant pathology (1963) at the University of California, Berkeley. He joined the Forest Service in 1960, and has been with the Station's research staff since then.

ACKNOWLEDGMENTS

I thank the following present or former members of the Forest Service, U.S. Department of Agriculture, for their assistance in this study: Neil MacGregor, for aid in planning and field operations; Ken Estes, Bill Paldi, Bill Schuener, Max Williamson, and Donald T. Gordon, for help in finding suitable study areas; and David A. Sharpnack and Liz Maxwell, for statistical consultation and services.

Dwarf Mistletoe-Infected Red Fir: growth after release

Robert F. Scharpf

CONTENTS

Page

Introduction 1

Methods 2

Results 4

  Radial Growth 4

  Height Growth 6

Discussion 6

Managing Released Stands 8

Literature Cited. 8

Pacific Southwest Forest and Range Experiment Station
P.O. Box 245
Berkeley, California 94701

June 1979

IN BRIEF...

Scharpf, Robert F.
1979. **Dwarf mistletoe-infected red fir: growth after release.** Res. Paper PSW-143, 9 p., illus. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

Retrieval Terms: Abies magnifica; release cuttings; height increment; radial growth; live crown ratio; *Arceuthobium abietinum.*

Release cutting—the logging of merchantable trees in stands of mixed size classes to provide growing space for smaller nonmerchantable trees—is currently a preferred method of harvest. Studies suggest that small fir trees respond well to release and that this method may have wide application for management of true firs in the Sierra Nevada and southern Cascade Ranges.

Many young- and old-growth stands, particularly red firs (*Abies magnifica* A. Murr.), however, are heavily infected with dwarf mistletoe (*Arceuthobium abietinum* f. sp. *magnificae*). Small fir seedlings and saplings in the understory are usually free or only lightly infected by dwarf mistletoe, whereas the larger poles and small sawtimber size class trees are often heavily infected. Previous research has shown that firs growing a foot or more in height will outgrow the vertical spread of dwarf mistletoe in the absence of overstory infection. In addition, trunk taper was not affected by an increase in levels of dwarf mistletoe infection in released red firs. To better manage dwarf mistletoe-infected stands in the Western United States, forest managers need answers to questions about the effects of release cutting and dwarf mistletoe on radial and height growth of infected trees.

In an attempt to find answers, field studies were begun in summer 1971 on four National Forests in northern California. The study areas represented the red fir forests of the Sierra Nevada and of the upper elevational zone of the southern Cascades. In the four forests, 2071 red firs were sampled. The following information was recorded for each test tree: (a) diameter-at-breast height, (b) live crown ratio, (c) height growth over the last 5 years, (d) mean annual radial growth the 5 years before release, (e) mean annual radial growth at 5-year intervals after release, and (f) dwarf mistletoe infection. It was expected that interacting variables—particularly tree diameter and live crown ratio—would influence growth response.

This paper reports the independent effects and interactions of release cutting, live crown ratio, diameter-at-breast height, and dwarf mistletoe on growth. Both infected and noninfected red firs responded well to release cutting: radial growth rate increased noticeably after 5 years, and essentially doubled 10 years after release. Higher rates of radial growth were achieved by trees with adequate live crown ratios and by trees with larger diameters. Dwarf mistletoe reduced radial growth significantly only at the medium-to-high levels of infection. Trees with a poor live crown ratio (40 percent or less live crown) grew less in height, and were less able to outgrow the vertical spread of dwarf mistletoe.

Release cutting is a practical method of managing dwarf mistletoe-infected red fir stands as long as adequate stocking remains after release. Selecting trees with good live crown ratios, preferably the larger, dominant trees, should be the main consideration, irrespective of the level of dwarf mistletoe infection. Results of this study should also apply to white fir (*Abies concolor* [Gord. and Glend.] Lindl.) infected with *A. abietinum* f. sp. *concoloris*.

True firs, principally white fir *(Abies concolor* [Gord. and Glend.] Lindl.) and red fir *(A. magnifica* A. Murr.), make up about one-fourth of the commercial sawtimber in California and contribute about the same proportion of growth (Oswald and Hornibrook 1966). A substantial portion of this growth and volume is in pure red fir stands. In the last decade, the stumpage value of firs has increased markedly and foresters are keenly interested in intensive management of these species.

Fir stands, particularly pure stands of old-growth red firs, were harvested in the past primarily by clearcutting. Clearcutting, especially of large blocks, required planting of trees to ensure adequate regeneration of the logged-over areas. Consistently good red fir nursery stock has not been available, and ponderosa pine (*Pinus ponderosa* Laws.) and Jeffrey pine (*P. jeffreyi* Grev. and Balf.) have been used, even though these species have not developed well on red fir sites. Where clearcutting is used today, the trend is toward cutting smaller blocks or narrow strips of mature trees to obtain natural regeneration from adjacent stands.

Many old-growth and younger merchantable fir stands in northern California contain abundant advance regeneration, or larger nonmerchantable trees. In these stands of mixed size classes, *release cutting* is usually the preferred method of harvest. The merchantable trees in stands of mixed size classes are harvested, thereby providing growing space for the smaller, residual nonmerchantable trees.

Gordon (1973) found that small firs respond well to release and that tree mortality after release is not a serious problem, even if some damage or injury to residual trees occurs. He suggested that release cutting may have wide application in the management of true firs in the Sierra Nevada and southern Cascade Ranges.

Many young- and old-growth fir stands, particularly red firs, are heavily infested with dwarf mistletoe (*Arceuthobium abietinum* Engelm. ex munz f. sp. *magnificae* Hawksworth and Wiens). Small firs in the understory (seedlings and saplings) are usually free, or only lightly infected by dwarf mistletoe (Scharpf 1969). Large, old-growth trees, the nonmerchantable larger trees, and poles remaining after release logging are often heavily infected.

Forest managers often ask questions about release of red fir stands infected with dwarf mistletoe. What is the effect of dwarf mistletoe? How fast will it spread among infected residual trees after release? Will infected trees release after logging? Will tree mortality or growth reduction be a problem over time in infested released stands?

Some of the above questions were answered recently (Scharpf and Parmeter 1976). On good sites, spread of dwarf mistletoe vertically within crowns of young, vigorous red firs and white firs not exposed to overstory infection, is slow, and the trees outgrow in height the vertical spread of the parasite by a ratio of at least 4 to 1. Dwarf mistletoe may not build up and spread throughout the crowns of young firs on good sites over the currently projected rotation ages of from 100 to 150 years. Scharpf (1977) found that trunk taper in red firs does not increase with an increase in dwarf mistletoe rating, as has been reported to occur with other dwarf mistletoe-host combinations (Baranyay and Safranyik 1970, Korstian and Long 1922). Tree taper differences, therefore, can be ignored in calculating growth and volume losses from dwarf mistletoe in true firs. Other questions regarding growth losses and mortality have not been answered to date.

This paper reports a study of the effects of dwarf mistletoe, release cutting, live crown ratio, and diameter-at-breast height on the growth of red fir. Dwarf mistletoe reduced radial growth significantly only at the medium-to-heavy levels of infection. Independent effects or interactions of the other three variables influenced the radial and height growth of both infected and noninfected stands.

METHODS

Height growth was not determined before release in this study because of the problems in determining the height of the tree at the time of release and in measuring the length of older internodes within the crown of test trees. In released trees, height growth over only the last 5 years was investigated.

Field studies extended from summer 1971 until fall 1972. Temporary plots were established on four National Forests where release logging had been done in red fir timber type *(table 1)*. The study areas represented the red fir forests of the upper elevational zone of the southern Cascades in northern California and the red fir forests of the Sierra Nevada.

Although site class was not determined for each study plot, measurements for the general areas of study ranged from site class II-150 to A-200 for dominant trees (Dunning 1942).

Size of the study plots varied, but each had to meet these research criteria:

a. About 100 or more released trees undamaged by logging and from 6 to 20 inches d.b.h. had to be available on each area after logging. Trees with broken tops, badly damaged crowns, or severe trunk wounds were rejected.

b. All trees selected for study had to be "fully" released. Whether trees were fully released was determined by the distance of the test trees to stumps of overstory trees removed during logging. Only test trees judged to have been suppressed in growth by overstory trees before release were selected for study. Groups of residual trees competing with one another, or trees not fully released after logging, were not sampled.

c. Dwarf mistletoe had to be present in all released stands studied, although not every released tree selected for study had to be infected. Trees that

Table 1—*Study area, elevation, trees sampled, and year of release cutting for released red firs in California*

National Forest and study area	Elevation *(Feet)*	Trees sampled	Year of release cutting
Lassen			
Swain Mt. Exp. Forest (T33, R8E)	6000	650	1960, 1962
Little Grizzly Creek (T26N, R5E)	6000		1955, 1966-1967
Tahoe			
Soda Springs (T16N, R14E)	7000	217	1955, 1958
Rattlesnake Creek (Sec. 22, 17N, R13E)	6500		1957-1958
Stanislaus			
Cabbage Patch (Hwy. 4, Sec. 29, T7N, R17E)	6500	642	1955-1956
Sierra			
Tamarack Ridge (Hwy. 168, Sec. 11 and 14, T9S, R25E)	6500	562	1956-1957

were within 100 feet of remaining infected overstory trees or within the margin in infested, uncut overstory were not selected as test trees.

One or more plots with arbitrary boundaries around each plot were established in each research area. All trees within a plot meeting the research criteria were sampled. For the four forests included in the study, 2071 red firs were sampled.

The following information was recorded for each test tree:

- *Diameter-at-breast height (d.b.h.).* For data analysis, trees were grouped into the following d.b.h. classes: 6.0 inches to 8.9 inches; 9.0 inches to 11.9 inches; 12.0 inches to 14.9 inches; 15.0 inches to 17.9 inches; and 18.0 inches to 20.9 inches.
- *Live crown ratio (LCR) proportion of the tree's height in living crown.* Dead and broken branches, thin portions of crown and similar irregularities were considered in the final judgment of live crown ratio. For data analysis, test trees were grouped into the following live crown ratio classes: 21 to 40 percent; 41 to 60 percent; 61 to 80 percent; and 81 to 100 percent live crown.
- *Height growth of the test trees over the last 5 years.* (This was done by measuring with a clinometer the length of the last five internodes between branch whorls.)
- *Mean annual radial growth the 5 years before release, and mean annual radial growth at 5-year intervals after release (B/A).* (If the last interval was less than 5 years, mean annual radial growth was determined from the number of growth rings that were present.) Radial growth measurements were determined from increment cores taken at d.b.h.
- *A dwarf mistletoe infection rating system (DMR).* Previously described by Scharpf (1977), the DMR was used as follows. The living crown was visually divided into thirds by height. Each third was rated as to its level of dwarf mistletoe infection: 0 = no infection; 1 = 1 to 10 percent of the primary branches infected; 2 = 11 to 50 percent of the primary branches infected; and 3 = 51 to 100 percent of the primary branches infected. The sum of the numbers listed for each portion of a tree crown gave an overall mistletoe infection rating. Trees with an overall rating of 0 were uninfected; 1 to 3 lightly infected; 4 to 6 moderately infected; and 7 to 9 heavily infected. This rating system is a modification of the 6-class dwarf mistletoe rating system commonly used today (Hawksworth 1977).

Analysis of radial growth was based on data from 1568 trees, and growth after release was based on data from the 5-to-10 year growth interval following release. For height growth, the same factors were used in the analysis of variance, except release, with results based on 2017 trees.

In addition to studying the effects of release and dwarf mistletoe on growth, it was expected that growth response would be influenced by other interacting factors, particularly tree diameter and live crown ratio. To determine if the factors investigated were significant sources of variation, the data were subjected to analysis of variance, including two-way interactions among the variables.

Table 2—*Table of F-values for independent effects and interactions of release, diameter-at-breast height, live crown ratio, and dwarf mistletoe rating on radial growth rate of red fir*

Variable	Degrees freedom	*F*
Independent Effects		
Before/after release (B/A)	1	371.00*
Diameter-at-breast height (d.b.h.)	4	20.47*
Live crown ratio (LCR)	3	50.56*
Dwarf mistletoe rating (DMR)	3	5.95*
Interactions		
B/A and d.b.h.	4	5.22*
B/A and LCR	3	8.09*
B/A and DMR	3	4.72*
d.b.h. and LCR	12	2.58*
d.b.h. and DMR	12	0.59
LCR and DMR	9	1.61

*Statistically significant at the 99 percent level of confidence.

RESULTS

Radial Growth

It is difficult to discuss the effect of any one factor on radial growth of red fir because analysis of the data showed that several factors influence growth. Analysis showed that the factors not only act alone but interact with one another to affect growth (*table 2*). I will attempt to point out, therefore, what I consider to be the important *independent* as well as *interacting* influences on radial growth.

Release

The most statistically significant and, perhaps, most important result of the study was that red firs responded well to release as expressed by a marked increase in radial growth rate. The magnitude of the growth response from an analysis of radial growth for all trees combined with different rated levels of dwarf mistletoe is shown in *figure 1*. Mean annual growth rates increased markedly within 5 years after release and essentially doubled after 10 years for both infected and uninfected trees. Available data was insufficient to determine precisely the growth rate 10 to 15 years after release. Preliminary results suggest, however, that growth, as influenced by release, more or less levels off in these later years.

Dwarf mistletoe was found to interact with release to affect radial growth rates in red firs (*fig. 1*). High, and to some extent, medium levels of dwarf mistletoe infection reduced growth rate. Before release, growth reduction from dwarf mistletoe may not have been as serious as after release. Under nonreleased conditions the trees (and probably the parasite) were not vigorous and were growing very slowly; thus, the effect of the parasite on growth was not pronounced. It is also possible that pronounced growth reduction by dwarf mistletoe on already weakened or severely suppressed nonreleased trees resulted in some mortality. Factors affecting mortality were not investigated in this study.

Although growth reduction from dwarf mistletoe occurred in released trees, the amount of reduction was noticeably offset by the increased growth as a result of release. It appears that increased radial growth takes place in both dwarf mistletoe infected and noninfected released red firs within 5 years of release, but that 5 to 10 years are needed before maximum growth rates as a result of release are achieved. After 10 years, no increases in growth rates were observed.

Live Crown Ratio

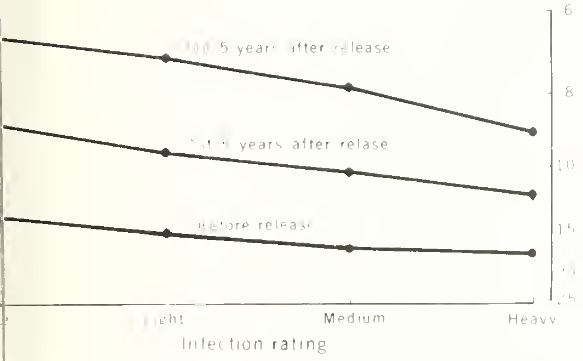
Next to release, live crown ratio was found to have the most significant effect on radial growth rate of red firs. It was apparent from the results that trees with good live crown ratios before and after release had better radial growth rates (*fig. 2*). This is because the capacity of a tree for photosynthesis, as expressed by the amount of living foliage, is an important factor in radial growth rate for trees growing under released stand conditions.

For released trees and probably also nonreleased trees, radial growth was related to the interaction of live crown ratio and d.b.h. In released trees, for example, radial growth generally increased with increases in live crown ratio and tree diameter (*fig. 3*). The larger, more dominant trees in a stand, on the average, had a greater live crown ratio than the smaller, suppressed understory. As a result, the larger trees had a competitive advantage because of their size, and a photosynthetic advantage because of higher live crown ratios. Because of these advantages, large trees exhibited higher radial growth rates than did smaller ones.

Results of the analysis showed that dwarf mistletoe did not interact with live crown ratio to affect radial growth, but the parasite exerted a signficant effect independently on growth rate before and after release. In released trees, for example, dwarf mistletoe reduced radial growth rate among all live crown ratio classes, especially at the level of infection rated heavy (*fig. 4*).

Even though dwarf mistletoe did not interact directly with live crown ratio to affect growth, the presence of the parasite was associated with some reduction in the live crown ratio. Heavy infection generally was found to reduce live crown ratios on an average of about 10 percent. Previous studies have shown that dwarf mistletoe-infected branches are a preferred infection site for the Canker fungus, *Cytospora abietis* Sacc., and that considerable crown reduction from branch killing occurs as a result of *Cytospora* infection (Scharpf 1964). At least part of the effect of dwarf mistletoe on radial growth in firs may be from reduction of live crown, and another part may be from the mistletoe's parasitic mode of life. The proportion that each of these two modes of action has on reducing radial growth was not determined in this study.

Dwarf mistletoe did not interact with d.b.h. to affect radial growth. In all d.b.h. classes, trees



gure 1—Red firs responded well to release as pressed by a marked increase in radial growth te. Dwarf mistletoe significantly reduced radial owth only at the medium-to-heavy levels of ection.

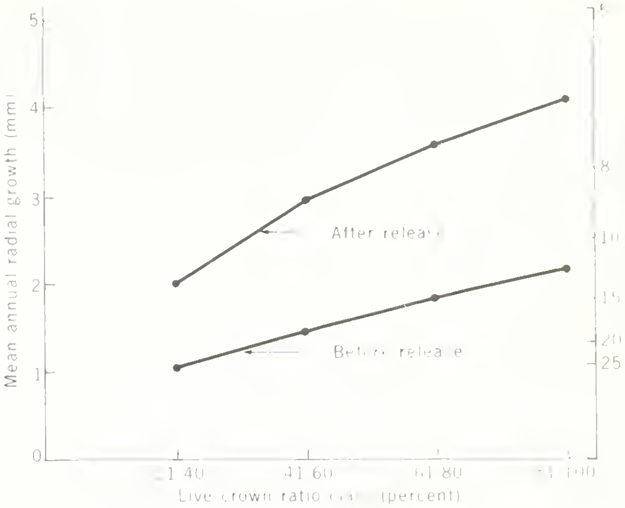
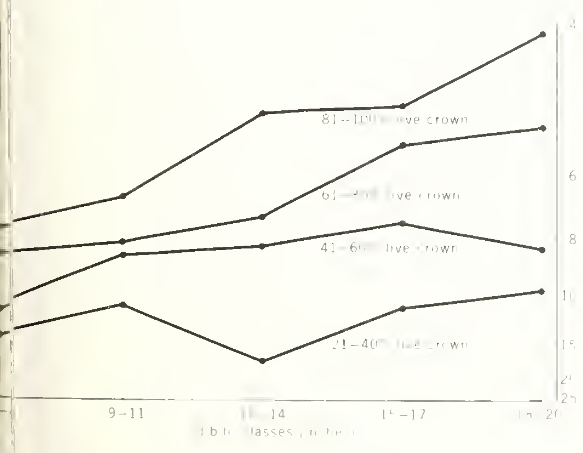


Figure 2—Next to release, live crown ratio had the most significant effect on radial growth rate of red firs. Trees with adequate live crown ratios, before and after release, had better radial growth rates.



Fgure 3—Live crown ratio and diameter-at-breast ight interacted to influence radial growth in reased red firs. Radial growth generally increased h increases in live crown ratio and tree diameter.

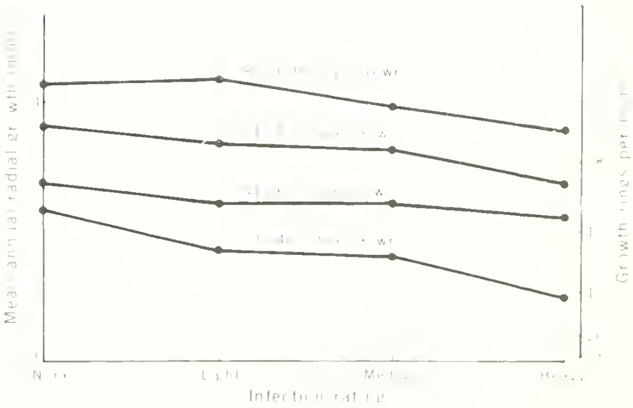


Figure 4—Dwarf mistletoe did not interact with live crown ratio but, independently, reduced radial growth rate among all live crown ratio classes in released trees, especially at the level of infection rated heavy.

Table 3—*Table of F-values for independent effects and interactions of live crown ratio, diameter-at-breast height, and dwarf mistletoe rating on 5-year height growth in released red fir*

Variable	Degrees freedom	F
Independent Effects		
Live crown ratio (LCR)	3	50.67*
Dwarf mistletoe rating (DMR)	3	23.51*
Diameter-at-breast height (d.b.h.)	4	9.14*
Interactions		
LCR and d.b.h.	12	1.39
d.b.h. and DMR	12	0.91
LCR and DMR	9	0.99

*Statistically significant at the 95 percent level of confidence.

with the highest levels of infection showed the greatest growth reduction.

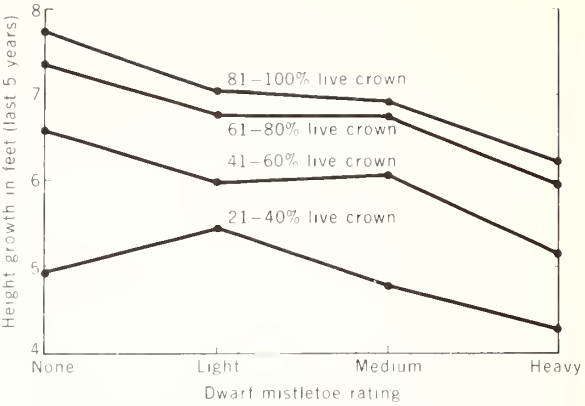


Figure 5—Most of the differences in height growth of trees resulted from differences in live crown ratio and degree of dwarf mistletoe infection. Trees with poor live crown ratio grew less in height, and were less able to outgrow the vertical spread of dwarf mistletoe.

Height Growth

As with radial growth, results showed that live crown ratio, dwarf mistletoe, and d.b.h. influenced height growth after release (*table 3*). None of these variables, however, interacted with one another to affect growth.

Most of the differences in height growth of trees in the study can be explained on the basis of differences in live crown ratio and dwarf mistletoe rating (*fig. 5*). Trees with poor live crown ratios, with or without dwarf mistletoe infection, on the average grew less than 1 foot a year in height. All other trees, irrespective of the level of dwarf mistletoe, were growing in height at an average of from 1 to 1.5 feet per year. In the absence of overstory infection, young trees growing in height of about 1 foot a year are able to outgrow the vertical spread of dwarf mistletoe by a ratio of at least 4 to 1 (Scharpf and Parmeter 1976). With such a ratio of growth-to-spread, infection levels and associated growth effects will diminish over time in heavily infected trees. With greater rates of height growth, infection levels and growth effects will diminish even more. Maintaining good height growth in released red firs is important in reducing future effects on growth from dwarf mistletoes.

Diameter-at-breast height was also found to be directly related to height growth. As explained previously, the larger trees are the more dominant, vigorous trees and, as such, grow taller more rapidly.

DISCUSSION

Results of this study indicate that both dwarf mistletoe infected and uninfected trees respond well to release logging. Why are infected red firs able to respond well to release and why do heavily infected trees often suffer relatively little growth impact? I suggest that several conditions are involved.

Suppressed firs have the inherent ability to respond to release and begin growth within a few years after release (Gordon 1973). This release response, expressed in particular by increased height growth, has an important bearing on effects from dwarf mistletoe. Studies on vertical spread of dwarf mistletoe in the crowns of red firs and white firs have shown that the parasite exerts little effect on growth if it is restricted to the lower portion of the crown (Scharpf and Parmeter 1976). Thus, over time, young firs on good sites "grow away" from infection and become less severely affected by dwarf mistletoe as long as adequate tree height growth is maintained.

Understory firs, even suppressed ones, often have a good live crown ratio. As this study has shown, live crown ratio had a marked effect on tree growth; however, dwarf mistletoe did not reduce the live crown ratio appreciably. Released firs, even those heavily infected by dwarf mistletoe, often have an abundant complement of foliage that is able to photosynthesize and produce the energy needed for maximum growth.

Red firs do not form brooms in response to infection, as do some other dwarf mistletoe-host species combinations. Hawksworth (1961), for example, found that reduction of radial growth was greater in broomed ponderosa pines in the southwest than in nonbroomed, infected trees, even though the nonbroomed trees may have had a higher rated level of dwarf mistletoe infection. The absence of pronounced dwarf mistletoe broom formation is probably a major reason for the lack of appreciable growth reduction on heavily infected red firs.

Is mortality a serious problem of infected red fir stands after release? Some trees could have died during that period after release, thereby adding another loss factor to those reported. Gordon (1973), however, attributed little (less than 1 percent) of the mortality which occurred in released, advance reproduction of red fir and white fir to dwarf mistletoe. I doubt if loss from mortality after release was of any consequence in this study, because trees of the size classes used that would have died within the 5 to 15 years after release would probably still have been standing on the plots, or would have fallen over in place. I saw little evidence of older or recently dead released trees on the study sites except for trees severely damaged as a result of logging. Permanent plots established at the time of the study will be used to determine mortality more precisely, as well as to assess changes in dwarf mistletoe infection rating and tree growth.

Will trunk swellings and cankers be of importance in released red fir stands? Trunk swellings and cankers caused by dwarf mistletoe in the main stem are recognized as a problem in infected red fir stands (Scharpf 1964, 1969). Considerable cull and tree breakage results from trunk infections, particularly in older trees. Recent studies suggest, however, that large swellings and cankers take many years to develop and may be of limited importance in managed, second-growth true fir stands.[1] Although verification is needed, it appears that trunk swellings have little effect on radial and height growth of released firs and that cull and tree breakage may be negligible over projected rotation ages for second-growth stands. In addition, studies have shown that, with present quality control procedures, no statistical differences were found in grade and volume of lumber cut from fir logs without dwarf mistletoe infection and from those with dwarf mistletoe trunk infections (Wilcox and others 1973).

One point must be considered in interpreting the results of this study and applying them directly to field conditions. The study was based mainly on *fully* released stand situations. Such stands may be below desirable stocking levels for particular management objectives. At any rate, the manager will be able to judge from this study the approximate range of growth he can expect from an infected red fir stand before release and from one fully released after logging. With the data given here, and with a knowledge of the general growth rate of stands of released trees in the field the manager can, within reason, predict future growth for individual fir stands with different levels of stocking. Efforts are being made to develop more precise growth and yield information for dwarf mistletoe infected and noninfected second-growth fir stands. Recent studies have shown that dwarf mistletoe has no statistically significant effect on trunk taper of released, pole-sized red firs (Scharpf 1977). Thus, the influence of dwarf mistletoe on tree form class likely will be of no consequence in determinations of growth and yield of released true fir stands.

The results of this study are not intended to suggest that dwarf mistletoe will not be a problem in released red firs. Some volume loss can be expected from growth reduction by the parasite, and unknown problems involving dwarf mistletoe may surface. It is well known, for example, that dwarf mistletoe predisposes trees to attack by bark beetles (Stevens and Hawksworth 1970). Also, the canker fungus *Cytospora abietis* often attacks and damages dwarf mistletoe-infected firs, and this fungus may become particularly serious in dwarf mistletoe infested stands when trees are injured by fire and logging, or weakened by adverse climatic conditions, such as drought stress (Scharpf 1964). The degree to which these conditions will influence released red firs infected with dwarf mistletoe, however, will be determined only from additional studies and from evaluation of permanent field plots.

The results of this study are applicable to dwarf mistletoe-infected white fir as well. The dwarf mistletoes on these two species are much alike in behavior and both red fir and white fir have similar silvical characteristics.

---

[1] Unpublished data by John R. Parmeter, Jr., on file, Department of Plant Pathology, University of California, Berkeley, Calif. 94720.

MANAGING RELEASED STANDS

Results of this study indicate that dwarf mistletoe-infected red fir stands can be managed by release cutting without serious losses from dwarf mistletoe. In deciding on this approach, the manager should consider:

- Release cutting implies that adequate advance regeneration will be present after logging on a given site. If this is the case, then release cutting should be considered as an appropriate management approach with or without dwarf mistletoe in the stand. If, however, release results in serious understocking, and planting or natural regeneration is required, then infected, released trees will act as a source of overstory infection. In such cases, regeneration over time will become severely infected unless nonsusceptible species of conifers seed-in or are planted. In selecting species for planting, remember that dwarf mistletoe on red fir is host specific and infects only red fir (and Noble fir in Oregon). Consider also that planted seedlings will take several years to become established and reach the initial size of the released residual trees. The growth loss that dwarf mistletoe will cause in released, understory trees over the rotation period, therefore, may be much less than the losses incurred from starting the stand anew with planted seedlings.
- It is best to leave as many uninfected or lightly infected trees or nonsusceptible species as possible to reduce volume losses that may occur over time, and to limit spread of the parasite within the residual stand.
- Live crown ratio is important to the subsequent growth response of released trees. Badly suppressed trees with poor live crown ratios show the poorest release response and suffer the most from dwarf mistletoe. Infected stands with primarily small, suppressed trees with poor live crown ratios might be managed by other methods.
- Most released trees on good sites will, after a few years, be putting on height growth faster than dwarf mistletoe can spread upward in the crown. Dwarf mistletoe infection after release and for a few years thereafter may appear serious, but with time should diminish. This change can be determined by assessing the rate of release response (annual height growth) in the residual trees. If the trees are growing well in height (about 1 foot or more per year), then the effect of dwarf mistletoe is diminishing and will become less of a problem until tree height growth slows.

LITERATURE CITED

Baranyay, J.A., and L. Safranyik
1970. **Effects of dwarf mistletoe on growth and mortality of lodgepole pine in Alberta.** Dep. Fish. and For., Can. For. Serv. Publ. 1285, 19 p.,illus.

Dunning, Duncan
1942. **A site classification for the mixed-conifer selection forests of the Sierra Nevada.** U.S. Forest Serv., Calif. Forest and Range Exp. Stn. Res. Note 28, 21 p., Berkeley, Calif.

Gordon, Donald T.
1973. **Released advance reproduction of white and red fir—growth, damage, mortality.** USDA Forest Serv. Res. Paper PSW-95, 12 p. illus., Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif.

Hawksworth, Frank G.
1961. **Dwarf mistletoe of ponderosa pine in the Southwest.** U.S. Dep. Agric. Tech. Bull. 1246, 112 p.,illus.

Hawksworth, Frank G.
1977. **The 6-class dwarf mistletoe rating system.** USDA Forest Serv. Gen. Tech. Rep. RM-48, 7 p. Rocky Mountain Forest and Range Exp. Stn., Fort Collins, Colo.

Korstain, C.F., and W.H. Long
1922. **The western yellow pine mistletoe.** U.S. Dep. Agric. Bull. 1112, 35 p.,illus.

Oswald, Daniel D., and E.M. Hornibrook
1966. **Commercial forest area and timber volume in California, 1963.** USDA Forest Serv. Resour. Bull. PSW-4, 16 p., Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif.

Scharpf, Robert F.
1964. **Dwarf mistletoe on true firs in California.** U.S. Dep. Agric. Forest Pest Leafl. 89, 7 p.,illus.

Scharpf, Robert F.
1969. **Dwarf mistletoe on red fir—infection and control in**

understory stands. USDA Forest Serv. Res. Paper PSW-50, 8 p. illus., Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif.

Sharpf, Robert F.
1977. **Dwarf mistletoe does not increase trunk taper in released red firs in California.** USDA Forest Serv. Res. Note PSW-326, 3 p. Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif.

Scharpf, Robert F., and J.R. Parmeter, Jr.
1976. **Population buildup and vertical spread of dwarf mistletoe on young red and white firs in California.** USDA Forest Serv. Res. Paper PSW-122, 9 p. Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif.

Stevens, Robert E., and Frank G. Hawksworth
1970. **Insects and mites associated with dwarf mistletoes.** USDA Forest Serv. Res. Paper RM-59, 12 p. Rocky Mountain Forest and Range Exp. Stn., Fort Collins, Colo.

Wilcox, Wayne W., W.Y. Pong, and J.R. Parmeter, Jr.
1973. **Effects of mistletoe and other defects on lumber quality in white fir.** Wood and Fiber 4(4):272-277.

The Forest Service of the U.S. Department of Agriculture

- . . . Conducts forest and range research at more than 75 locations from Puerto Rico to Alaska and Hawaii.
- . . . Participates with all State forestry agencies in cooperative programs to protect and improve the Nation's 395 million acres of State, local, and private forest lands.
- . . . Manages and protects the 187-million-acre National Forest System for sustained yield of its many products and services.

The Pacific Southwest Forest and Range Experiment Station

represents the research branch of the Forest Service in California and Hawaii.

1979. **Dwarf mistletoe-infected red fir: growth after release.** Res. Paper PSW-143, 9 p., illus. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

Release cutting, live crown ratio, diameter-at-breast height, and dwarf mistletoe *(Arceuthobium abietinum* f. sp. *magnificae).* acted to affect radial and height growth of red firs *(Abies magnifica* A. Murr.). Infected and noninfected red firs responded well to release as expressed by increased radial growth: growth rate doubled within 10 years after release. Live crown ratio also had a marked effect on radial growth rate. Irrespective of the level of dwarf mistletoe, trees with good live crown ratios showed significantly greater rates of radial growth than did trees with poor live crown ratios. Dwarf mistletoe reduced growth but, in general, growth was reduced significantly only at the medium-to-high levels of infection. Height growth in released trees was influenced most by live crown ratio and, to a lesser extent, by dwarf mistletoe and tree diameter. In managing red fir stands by release cutting, trees with good live crown ratios, preferably the larger ones, should be left in the stand, regardless of the level of dwarf mistletoe infection.

Retrieval Terms: Abies magnifica; release cuttings; height increment; radial growth; live crown ratio; *Arceuthobium abietinum.*

1979. **Dwarf mistletoe-infected red fir: growth after release.** Res. Paper PSW-143, 9 p., illus. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

Release cutting, live crown ratio, diameter-at-breast height, and dwarf mistletoe *(Arceuthobium abietinum* f. sp. *magnificae).* acted to affect radial and height growth of red firs *(Abies magnifica* A. Murr.). Infected and noninfected red firs responded well to release as expressed by increased radial growth: growth rate doubled within 10 years after release. Live crown ratio also had a marked effect on radial growth rate. Irrespective of the level of dwarf mistletoe, trees with good live crown ratios showed significantly greater rates of radial growth than did trees with poor live crown ratios. Dwarf mistletoe reduced growth but, in general, growth was reduced significantly only at the medium-to-high levels of infection. Height growth in released trees was influenced most by live crown ratio and, to a lesser extent, by dwarf mistletoe and tree diameter. In managing red fir stands by release cutting, trees with good live crown ratios, preferably the larger ones, should be left in the stand, regardless of the level of dwarf mistletoe infection.

Retrieval Terms: Abies magnifica; release cuttings; height increment; radial growth; live crown ratio; *Arceuthobium abietinum.*

Scharpf, Robert F.
1979. **Dwarf mistletoe-infected red fir: growth after release.** Res. Paper PSW-143, 9 p., illus. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

Release cutting, live crown ratio, diameter-at-breast height, and dwarf mistletoe *(Arceuthobium abietinum* f. sp. *magnificae)* acted to affect radial and height growth of red firs *(Abies magnifica* A. Murr.). Infected and noninfected red firs responded well to release as expressed by increased radial growth: growth rate doubled within 10 years after release. Live crown ratio also has a marked effect on radial growth rate. Irrespective of the level of dwarf mistletoe, trees with good live crown ratios showed significantly greater rates of radial growth than did trees with poor live crown ratios. Dwarf mistletoe reduced growth but, in general, growth was reduced significantly only at the medium-to-high levels of infection. Height growth in released trees was influenced most by live crown ratio and, to a lesser extent, by dwarf mistletoe and tree diameter. In managing red fir stands by release cutting, trees with good live crown ratios, preferably the larger ones, should be left in the stand, regardless of the level of dwarf mistletoe infection.

Retrieval Terms: Abies magnifica; release cuttings; height increment; radial growth; live crown ratio; *Arceuthobium abietinum.*

Scharpf, Robert F.
1979. **Dwarf mistletoe-infected red fir: growth after release.** Res. Paper PSW-143, 9 p., illus. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

Release cutting, live crown ratio, diameter-at-breast height, and dwarf mistletoe *(Arceuthobium abietinum* f. sp. *magnificae)* acted to affect radial and height growth of red firs *(Abies magnifica* A. Murr.). Infected and noninfected red firs responded well to release as expressed by increased radial growth: growth rate doubled within 10 years after release. Live crown ratio also has a marked effect on radial growth rate. Irrespective of the level of dwarf mistletoe, trees with good live crown ratios showed significantly greater rates of radial growth than did trees with poor live crown ratios. Dwarf mistletoe reduced growth but, in general, growth was reduced significantly only at the medium-to-high levels of infection. Height growth in released trees was influenced most by live crown ratio and, to a lesser extent, by dwarf mistletoe and tree diameter. In managing red fir stands by release cutting, trees with good live crown ratios, preferably the larger ones, should be left in the stand, regardless of the level of dwarf mistletoe infection.

Retrieval Terms: Abies magnifica; release cuttings; height increment; radial growth; live crown ratio; *Arceuthobium abietinum.*

PACIFIC SOUTHWEST
Forest and Range
Experiment Station

SERVICE
ARTMENT OF AGRICULTURE

ffects of Aerially Applied Mexacarbate n Western Spruce Budworm Larvae nd their Parasites in Montana

Carroll B. Williams, Jr.   Patrick J. Shea   Mark D. McGregor

CLEMSON UNIVERSITY LIBRARY
MAR 31 1980
SCI., TECH. & AGR. DIV.

RESEARCH PAPER PSW- 144

The Authors

CARROLL B. WILLIAMS, JR., is a pioneer scientist studying integrated management systems for forest insect pests and diseases, with headquarters in Berkeley, Calif. He is a University of Michigan graduate (B.S. in forestry, 1955; M.S., 1957; and Ph.D. in forest entomology, 1963). He joined the Forest Service in 1957. **PATRICK J. SHEA** is in charge of the Station's field evaluation of chemical insecticides, with headquarters at Davis, Calif. He joined the Forest Service and Station staff in 1967. He earned degrees (B.S., 1962; M.S., 1972) in entomology at the University of California, Berkeley. **MARK D. McGREGOR** earned B.S. (1959) and M.S. (1962) degrees in entomology at Utah State University. He is in charge of bark beetle evaluation and control in the Forest Service's Northern Region, with headquarters in Missoula, Mont. He has been with the Forest Service since 1957.

Effects of Aerially Applied Mexacarbate on Western Spruce Budworm Larvae and their Parasites in Montana

Carroll B. Williams, Jr. Patrick J. Shea Mark D. McGregor

CONTENTS

	Page
Introduction	1
Materials and Methods	2
Study Areas and Treatments	2
Laboratory Procedures	3
Results and Discussion	4
The 1965 Tests	4
The 1966 Tests	6
The 1968 Tests	7
Parasitism in the 1968 Tests	9
Conclusions	13
Literature Cited	13

Pacific Southwest Forest and Range Experiment Station
P.O. Box 245
Berkeley, California 94701
June 1979

IN BRIEF...

Williams, Carroll B., Jr., Patrick J. Shea, and Mark D. McGregor. 1979. **Effects of aerially applied mexacarbate on western spruce budworm larvae and their parasites in Montana.** Res. Paper PSW-144, 14 p. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

Retrieval Terms: Insecticides; mexacarbate; naled; *Choristoneura occidentalis; Apanteles fumiferanae; Glypta fumiferanae; Phaeogenes hariolus; Mesochorus;* tachinids.

In 1965, 1966, and 1968, mexacarbate was aerially applied against western spruce budworm larvae (*Choristoneura occidentalis* Freeman) in budworm-infested forests of the Bitterroot National Forest in Montana. These field tests were designed to help assess mexacarbate, a nonpersistent insecticide, as a possible replacement for DDT. The tests would also provide opportunities for a study of spray distribution and spray droplet sizes as they relate to budworm mortality, and of the effects of mexacarbate on primary parasites of western spruce budworm larvae and other nontarget organisms, including several species of small mammals, birds, grouse, and fish, and fish habitat. The 1968 tests also included use of a nitrogen-pressurized spray system and evaluation of the process of atmospheric transport and diffusion which uses natural air movements to disseminate spray droplets throughout target areas. In 1969, the U.S. Environmental Protection Agency registered mexacarbate for use in suppressing the western spruce budworm.

The 1965 and 1966 mexacarbate applications were made in several drainages to the Bitterroot River. Treatment at the rate of 0.15 lb a.i./gal/acre (68.04 g a.i./3.785 l/0.404 ha) killed about 90 percent of the budworm larvae. Parasitized budworm larvae survived the treatments better than nonparasitized larvae. The overwintering parasites, *Apanteles fumiferanae* Viereck and *Glypta fumiferanae* Viereck, accounted for most of the subsequent increase in parasitism. The late larval, pupal parasites, primarily *Phaeogenes hariolus* (Cresson), *Mesochorus* sp., and tachinids also increased.

The 1968 tests were made on budworm-infested forests in two areas within the Blackfoot River drainage, east of Missoula, Montana. Mexacarbate, applied at the rate of 1 oz a.i./pt/acre (28.35 g a.i./473.16 ml/0.404 ha), suppressed 71 percent of the budworm populations in one area and 53 percent in the other.

In the 1965 and 1966 tests, parasitism increased in surviving budworm larvae of the treated generations, but tended to return to pretreatment levels the next year. In the 1968 tests, parasitism increased significantly in the areas of lowest budworm mortality and remained significantly higher than the 1968 prespray level for up to 2 years after treatment.

The 1965 and 1966 tests were considered successful in that the treatments killed about 90 percent of the budworm, but the 1968 tests were considered a failure in that less than 90 percent were killed. Higher parasite survival in the 1968 tests, however, provided unexpected information on several common parasites of the western spruce budworm.

The results suggest the possibility that nonpersistent insecticides can be used to reduce directly epidemic budworm populations and to increase the ratio of parasites to budworm, thereby increasing parasite efficacy in control of budworm populations for several years after treatment.

Since 1969, mexacarbate has been officially registered by the U.S. Environmental Protection Agency (EPA) for use in suppression of the western spruce budworm (*Choristoneura occidentalis* Freeman), a major defoliator in Western United States. Leading to this registration were field tests which showed mexacarbate as an effective replacement for DDT in the suppression of budworm populations.

In 1965, a field test of naled and mexacarbate (Zectran)[1] against western spruce budworm larvae in several drainages of the Bitterroot National Forest in Montana, indicated that mexacarbate was a highly promising replacement for DDT. Naled was not as effective as mexacarbate in that budworm mortality was less. When applied at the rate of 0.15 lb a.i./gal/acre (68.04 g a.i./3.785 l/ 0.404 ha), mexacarbate suppressed the budworm population by about 92 percent (Williams and Walton 1968). Data indicated that mexacarbate was more toxic to western spruce budworm larvae than to larvae of associated defoliators (Williams and Walton 1968). Data also indicated that the mexacarbate treatment did not seriously affect the major parasites of western spruce budworm larvae during and immediately after spraying (Williams and others 1969).

On the basis of results of the 1965 field test, a pilot test of mexacarbate was made in early spring, 1966, on two additional budworm infested forests in the Bitterroot National Forest. Major objectives of this test were:

a. To test further mexacarbate at the dosage rate of 0.15 lb a.i./gal/acre (68.04 g a.i./3.785 l/ 0.404 ha) for suppressing western spruce budworm larval populations.

b. To provide opportunites for research scientists to try newer methods to more thoroughly investigate spray distribution, spray droplet sizes, and their relations to mortality in populations of budworm larvae.

c. To continue monitoring the effects of mexacarbate applications on primary parasites of western spruce budworm larvae, and other nontarget organisms (including several species of small mammals, birds, grouse, fish), and fish habitat.

In 1968, another pilot test was conducted in two areas within the Blackfoot River Drainage east of Missoula, Montana. Objectives of this test were:

a. To determine if mexacarbate applied at 1 ounce a.i./1 pt carrier/acre (28.35 g a.i./473.16 ml/0.404 ha) could effectively suppress western spruce budworm larval populations.

b. To test a nitrogen-pressurized spray system for applying insecticides.[2]

c. To apply the process of atmospheric transport and diffusion to cover the target areas.

---

[1] This publication reports research involving pesticides. It does not contain recommendations for their use, nor does it imply that the uses discussed here have been registered. All uses of pesticides must be registered by appropriate State and/or Federal agencies before they can be recommended.

[2] The nitrogen-pressured spray system was used to break up the insecticide spray mass into small droplets. It proved to be ineffective as the spray cloud could not be delivered into the target areas and this resulted in poor coverage.

Some results of these pilot tests in 1966 and 1968 have been published or summarized. Descriptions of the operational phases were summarized by Honing (1968) for the 1966 test, and by McGregor and Dewey (1968) for the 1968 test. Relationships between spray distribution, spray droplet size, and budworm mortality were described in a series of articles (Himel and Moore 1967; Himel 1969a; Himel and Moore 1969; Himel 1969b; and Buffam and others 1967). The effects of mexacarbate applications on nontarget organisms have been described for small mammals and birds (Pillmore and others 1971), for blue grouse (Mussehl and Schladweiler 1969), and for aquatic organisms (Graham and Gould 1967). This information and similar findings from other tests and studies provided the supportive base for the subsequent registration of mexacarbate with the U.S. Environmental Protection Agency (EPA) for the control of spruce budworms, *Choristoneura* sp. The studies reported here attempted to discern the effects of various mexacarbate treatments on major parasites of budworm larvae immediately following spraying and for 2 years thereafter.

Although at this writing mexacarbate is registered for budworm suppression, its manufacture has been discontinued. Nevertheless, we believe the effects of mexacarbate treatments on budworm parasites merits publication for the following reasons:

a. The chemical structure and insecticidal properties of mexacarbate closely resemble those of aminocarb (Matacil), another carbamate insecticide (Lyon 1976, Randall 1976). The studies reported here for mexacarbate have relevance for aminocarb. Aminocarb has replaced mexacarbate for control of the spruce budworm in Canada and may be registered in the United States.

b. These studies provide the basic data to describe the interaction of an insecticide with the host insect and its parasites. Results of these studies will be useful to those scientists who will be asked to develop an integrated pest management program for the western spruce budworm.

This paper describes the 1965, 1966, and 1968 mexacarbate applications and the 2 years of population sampling to determine amount of parasitism following treatments—a total of 6 years of field study (1965-1970).

MATERIALS AND METHODS

Study Areas and Treatments

All mexacarbate applications for these studies were made in budworm infested forests in Montana. These forests were largely a mixture of Douglas-fir (*Pseudotsuga menziesii* var. *glauca* [Beissn.] Franco); Engelmann spruce (*Picea engelmanii* Parry); subalpine fir (*Abies lasiocarpa* [Hook.]); and grand fir (*A. grandis* [Dougl.] Lindl.). Ponderosa pine (*Pinus ponderosa* [Laws.]), a nonhost tree, occurred in substantial numbers on the dry, exposed sites. Douglas-fir was the most common host tree present.

The 1965 and 1966 mexacarbate applications were made in various drainages to the Bitterroot River in the Bitterroot National Forest. The 1965 tests occurred within four areas, each about 100 acres (40.5 ha), in the west fork of the Bitterroot River. Mexacarbate was aerially applied to budworm infested trees in Tough Creek at the rate of 0.15 lb a.i./gal/acre (68.04 g a.i./3.785 l/0.404 ha). Naled, an organophosphate insecticide, was applied in a low-volume concentrate of ethylene glycol at the rate of 0.41 lb a.i./0.82 pt/acre (185.97 g a.i./0.388 l/0.404 ha) to budworm infested trees in Mud Creek. Two drainages, One-Two Creek and Blue Joint Creek, served as checks. Budworm larval populations were sampled on 184 trees divided among the four drainages. The same trees were used throughout the 3-year study period. In 1965, budworm populations were sampled twice, 24 hours before treatment and again 7 days later. An extension pole pruner with a collecting bag attached just below the cutting head was used to cut two 15-inch (38-cm) branches from each crown third of each of the study trees. A total of six branches were cut from each study tree for each sampling period during 1965, 1966, and 1967. In 1966 and 1967, populations on study trees were sampled only once. Population sampling for all 3 years occurred when most budworms were in 5th and 6th instars, the age at which they are most exposed. Younger and smaller budworms are hidden by foliage or are mining the buds.

The 1966 tests were conducted on larger study areas within the Bitterroot River drainages. Mexacarbate was aerially applied at the rate of 0.15 lb a.i./gal/acre (68.04 g a.i./3.785 l/0.404 ha) to budworm infested trees in Trapper Creek, an approximate 5000-acre (2020-ha) drainage on the West Fork of the Bitterroot River, 11 miles southwest of Darby, Montana. The treatment was replicated on a 2000-acre (808.0-ha) infested stand in Laird Creek in the East Fork of the Bitterroot River. Two drainages—Violet Creek in the West Fork, and Andrews Creek in the East Fork of the Bitterroot River—served as check areas. Budworm populations were sampled 24 hours before treatment and again 5 and 10 days later using the same sampling procedures described for the 1965 tests. In 1967, populations were sampled only once. Because of limitations of personnel and field laboratory space, the parasite studies were done with budworm collected from 120 trees in the Trapper Creek drainage and 55 trees in the Violet Creek drainage.

The 1968 tests were conducted on budworm infested forests in two areas within the Blackfoot River drainage east of Missoula, Montana. Mexacarbate was aerially applied to 2912 acres (1176.4 ha) in the Burnt Fork of Belmont Creek and to 3168 acres (1279.9 ha) in Chamberlain Creek. A third area, located 20 miles (32.2 km) west of Chamberlain Creek and 12 miles (19.3 km) south of Belmont Creek, served as a check area. The insecticide formulation was mixed with Freon 12 at a 1:1 ratio and expelled from a nitrogen-pressurized spray system to produce a droplet spectrum having a volume median diameter (VMD)[3] of 60_{μ} (U.S. Forest Service 1972). The aerial application technique was based on the concept of atmospheric transport and diffusion which uses the natural air movements in the drainage to disseminate droplets throughout the target area (Parker 1967).

In 1968, budworm populations were sampled 2 and 3 days before treatment by cutting four 15-inch (38-cm) branches from the midcrown of the study trees, and again 4 days after treatment with sixteen 15-inch (38-cm) branches cut from the midcrown of the study trees. In 1969 and 1970, budworm populations were sampled only once using four 15-inch (38-cm) branches from the midcrown of the study trees. Sampling for all 3 years was done when the majority of the budworm were 5th and 6th instars, and the same 40 trees in each area were sampled during the 3-year study period. The change in sampling procedures for the 1968 tests followed analyses of the 1965-1967 budworm sampling data which indicated that budworm population densities on branches from the midcrown of study trees were the approximate average densities for the entire tree crown. The data analyses also indicated that four branches per tree were a sufficient sample in order to be within a 10 percent sampling error for the expected prespray population levels, and that 16 branches would be required for the anticipated postspray population levels in order to be within a 10 percent sampling error.

Laboratory Procedures

All sample branches with their resident insects were transferred to polyethylene bags and coded for study area, plot, tree, and crown level. Samples were placed in a walk-in refrigerator held at 40° to 45°F (4.44° to 7.22°C) and stored overnight. All insects were removed from the sample branches and bags the following day, separated by species, and counted at the field laboratory. Buds or shoots on each sample branch were counted and the length and width of each branch recorded.

All budworm larvae found in each sample were placed for rearing into 100-by-25 mm plastic petri dishes containing artificial diet (Lyon and others 1972). Ten larvae were placed in a dish. Dishes were examined periodically and diet replaced as needed. Nonparasitized larvae completed their development and adult moths emerged in the petri dishes. All budworms completing development were recorded. Mature parasites emerging from larvae were removed from the petri dishes and placed into gelatin capsules. Larvae and pupae from which neither adults nor parasites emerged were dissected for parasites. The parasites were first identified by using a key (Wilson and Bean 1964) and then by comparing them with identified specimens obtained from Colorado and Minnesota collections. The incidence of parasitism of budworm populations was determined by recording number of parasites that emerged from larvae rearings or were discovered by dissection, and was expressed as a ratio of number of parasites per 100 budworm larvae. The words "incidence of parasitism" and "parasitism" are used interchangeably in the text and refer to the ratio of parasites to budworm larvae.

---

[3] The theoretical center of the spray droplet size spectrum, i.e., half of the spray mass is in droplets larger than the VMD and half in droplets smaller than the VMD.

RESULTS AND DISCUSSION

The 1965 Tests

Mexacarbate applied at the rate of 0.15 lb/a.i./gal/acre (68.04 g a.i./3.785 l/0.404 ha) was more effective (99 percent confidence level) than naled applied at the rate of 0.41 lb a.i./0.82 pt/acre (185.97 g a.i./0.399 l/0.404 ha) in suppressing budworm populations in 1965 field tests (*table 1*). In 1966, however, budworm populations began declining in study areas from unknown causes. Nevertheless, in 1966, population densities in the mexacarbate-treated area (Tough Creek) remained significantly lower (at the 95 percent confidence level) than population densities in the other three areas. By 1967, the last year of budworm sampling, population densities in one of the check areas (Blue Creek) had declined to the level of populations in Tough Creek, and these populations were significantly lower than those in the other two areas.

The 1965 insecticide treatments appeared to have different effects on the various groups of parasites of the western spruce budworm. No lasting effects were observed on the two overwintering parasites—the braconid *Apanteles fumiferanae* Viereck and the ichneumonid *Glypta fumiferanae* Viereck. Parasitism by *A. fumiferanae* increased significantly (at the 99 percent confidence level) in the 1965 posttreatment budworm population in the mexacarbate treated area, whereas, no significant difference in parasitism by *A. fumiferanae* was found between the pretreatment, and posttreatment budworm populations among the other study areas (*table 2*). Parasitism by *A. fumiferanae* returned to the 1965 pretreatment levels by 1966, and no *A. fumiferanae* were recovered from either Tough Creek or Blue Joint Creek in 1967. Because of the low budworm population densities in these two areas (*table 1*) in 1967, it is not surprising that *A. fumiferanae* were difficult to detect or recover. Seven *A. fumiferanae,* however, were recovered in 1967 from budworm populations collected from Mud Creek (*table 2*).

Parasitism by *G. fumiferanae* was similar before and after treatments in 1965 in all four areas (*table 2*). It declined in 1966 at Mud Creek, the naled-treated area, and at Blue Joint, a check area, but sparse host populations in most of the study areas the following year prevented evaluation of parasitism by *G. fumiferanae,* except to show that it was present (*table 2*).

Table 1—*Trees sampled and estimates of western spruce budworm (Choristoneura occidentalis Freeman) larval populations before and after 1965 insecticide treatments, and for 2 years following in the study areas*

Treatment and study area	Trees	1965		1966	1967
		Prespray estimate	Postspray estimate	Estimate (1 year)	Estimate (2 years)
		Larvae per 1000 square inches branch surface[1]			
Mexacarbate:					
Tough Creek	56	[2]37.8[3](3.3)	[4]4.1 (0.9)	[5]2.44 (0.30)	0.42 (0.08)
Naled:					
Mud Creek	43	43.8 (4.5)	23.0 (3.1)	8.87 (1.02)	1.04 (0.27)
Controls:					
One-Two Creek	45	44.1 (3.7)	32.7 (2.6)	8.16 (0.85)	2.52 (0.32)
Blue Joint Creek	40	33.0 (3.5)	22.4 (2.5)	5.64 (0.56)	0.54 (0.13)

[1] *C. occidentalis* larvae per 1000 square inches (6451.6 square cm) branch surface.

[2] Prespray population estimates among the study areas are not significantly different at the 95 percent confidence level, according to t-tests.

[3] Values in parentheses are standard errors (SE).

[4] The estimate is significantly different at the 99 percent level from the postspray estimates of the other study areas.

[5] The estimate is significantly different at the 95 percent level from those in the other study areas.

Table 2—*Estimates of parasitism of western spruce budworm (Choristoneura occidentalis Freeman) by the early larval parasites, Apanteles fumiferanae and Glypta fumiferanae, and late larval, pupal parasites, Phaeogenes hariolus and tachinids, before and after 1965 insecticide treatments, and for 2 years following in the study areas.*

	1965				1966		1967	
Treatment and study area	Prespray estimate[1,2]	Parasites reared	Postspray estimate[1,2]	Parasites reared	Estimate[1] (1 year)	Parasites reared	Estimate[1] (2 years)	Parasites reared
				Apanteles fumiferanae				
Mexacarbate:								
Tough Creek	[4]5.46 [3](0.59)	124	[5]15.10 (2.70)	29	[4]4.46 (1.60)	7	— —	—
Naled:								
Mud Creek	3.42 (0.59)	56	1.92 (0.52)	18	2.63 (0.83)	11	8.25 (3.59)	7
Check:								
One-Two Creek	3.55 (0.57)	75	4.18 (0.73)	56	2.58 (0.80)	12	1.90 (1.80)	3
Check:								
Blue Joint Creek	3.75 (0.68)	44	2.55 (0.61)	22	1.21 (0.70)	3	— —	—
				Glypta fumiferanae				
Mexacarbate:								
Tough Creek	[4]8.46 (0.77)	192	5.73 (1.41)	11	8.92 (2.56)	14	[4]7.41 (5.19)	2
Naled:								
Mud Creek	9.46 (0.94)	155	8.65 (1.03)	81	2.87 (1.03)	12	4.71 (2.42)	4
Check:								
One-Two Creek	10.76 (1.02)	277	9.85 (0.97)	132	13.09 (2.25)	61	6.96 (1.98)	11
Check:								
Blue Joint Creek	8.00 (1.07)	94	7.64 (1.09)	66	2.02 (0.90)	5	7.69 (4.80)	2
				Tachinids				
Mexacarbate:								
Tough Creek	1.15 (0.33)	26	0.52 (0.53)	1	— —	—	3.70 (3.73)	1
Naled:								
Mud Creek	0.67 (0.24)	11	0.64 (0.26)	6	0.24 (0.24)	1	3.53 (2.40)	3
Check:								
One-Two Creek	3.79 (0.59)	80	4.49 (0.67)	60	2.79 (0.82)	13	— —	—
Check:								
Blue Joint Creek	8.26 (1.03)	97	5.90 (0.90)	51	3.24 (1.28)	8	— —	—
				Phaeogenes hariolus				
Mexacarbate:								
Tough Creek	1.32 (0.32)	30	[5]11.46 (3.25)	22	— —	—	— —	—
Naled:								
Mud Creek	0.55 (0.23)	9	0.75 (0.32)	7	— —	—	— —	—
Check:								
One-Two Creek	0.28 (0.11)	6	[5]2.16 (0.43)	29	0.64 (0.37)	3	— —	—
Check:								
Blue Joint Creek	0.60 (0.25)	7	[6]3.70 (0.86)	32	— —	—	— —	—

[1] Parasitism is expressed as the number of parasites per 100 budworm *(C. occidentalis)*.

[2] Estimate from populations sampled 24 hours before treatment; postspray estimate from populations sampled 7 days after treatment.

[3] Values in parentheses are standard errors (SE).

[4] Sample period estimates for the incidence of parasitism among the study areas not significantly different at the 95 percent confidence level, according to t-tests.

[5] Significantly different from the prespray estimate at the 99 percent confidence level, according to t-tests.

[6] Significantly different from the prespray estimate at the 95 percent confidence level, according to t-tests.

The incidence of parasitism of western budworm larvae by tachinids was highly variable among the study areas before the treatments and, after the treatments, was much lower in the insecticide-treated areas than in the check areas. Tachinids seemed to be affected adversely by mexacarbate (*table 2*). This situation is suggested by the few reared from posttreatment budworm collections in 1965 and 1966, particularly in the mexacarbate-treated area, and also by the decline in parasitism in the treated areas in 1965 and 1966 compared with the relative stability of parasitism in the check areas. Tachinids were attacking budworm larvae at treatment time and, therefore, were more vulnerable to the insecticides than were *A. fumiferanae* and *G. fumiferanae*. These two overwintering parasites attacked 1st and 2nd instar budworm larvae the preceding fall, overwintered in the larvae, and had not yet emerged at treatment time. No tachinids were recovered in 1966 from budworm larvae collected from the 1965 mexacarbate-treated area (Tough Creek), and only one was recovered from the naled-treated area (Mud Creek). Although parasitism by tachinids differed (95 percent level) between the check areas in 1965, it was similar in 1966. Few tachinids were recovered from all areas in 1966, and only four tachinids were recovered from the four study areas in 1967—three from Mud Creek and one from Tough Creek. None was recovered from any of the check areas which contained the higher number of tachinids the previous 2 years.

Another parasite, *Phaeogenes hariolus* (Cresson), attacked budworm larvae at the time treatments were applied. A significant increase in parasitism by *P. hariolus* in the postspray budworm populations occurred in three areas (*table 2*). The increase was statistically significant at the 99 percent confidence level in Tough Creek and One-Two Creek, and at the 95 percent level in Blue Joint. No significant increase in parasitism by *P. hariolus* was found in Mud Creek. Only three *P. hariolus* were recovered from budworm populations in 1966; none was recovered in 1967.

Both tachinids and *P. hariolus* were flying and attacking budworm larvae at the time of treatment, but only the tachinids appeared to have been harmed by mexacarbate. Apparently *P. hariolus* was not affected, and its parasitism of budworm larvae increased significantly in the mexacarbate-treated area and in the check areas. But *P. hariolus* was practically absent from all four areas in the 2 years following spraying.

The 1966 Tests

Mexacarbate applied, at the rate of 0.15 lb a.i./gal/acre (68.04 g a.i./3.785 1/0.404 ha) severely suppressed budworm populations in Trapper Creek—up to 95 percent 5 days after treatment *(table 3)*. Mortality remained essentially the same by the 10-day postspray sampling period. Budworm mortality in the Violet Creek check area was 46 percent by 5 days and 64 percent by 10 days postspray *(table 3)*. Prespray budworm populations were similar in Trapper and Violet

Table 3—*Estimated population densities of western spruce budworm (Choristoneura occidentalis Freeman) before and after 1966 mexacarbate treatments, percent mortality following treatments, and 1967 estimated population densities*

Study area and treatment	Trees	1966					1967
			(5 days)		(10 days)		
		Prespray estimate[1]	Postspray estimate[1]	Mortality	Postspray estimate[1]	Mortality	Estimate[1] (1 year)
				Percent		*Percent*	
Trapper Creek (Mexacarbate)	120	27.90 [2](1.42)	[3]1.36 (0.17)	95.14 (0.67)	[3]1.20 (0.18)	94.24 (0.99)	4.51 (0.44)
Violet Creek (Check)	55	22.28 (1.45)	11.87 (0.93)	46.03 (3.49)	6.82 (0.89)	64.00 (4.06)	6.13 (0.57)

[1] Number of budworm (*C. occidentalis*) per 1000 square inches (6451.6 square cm) branch surface.

[2] Values in parentheses are standard errors (SE).

[3] Population density of mexacarbate-treated area significantly different from that in the check area at 99 percent confidence level.

Creeks but were significantly different (99 percent confidence level) at the 5- and 10-day postspray samples. This difference in budworm population densities between the two areas in 1967 was not significant *(table 3)*.

Parasitism of budworm populations by *A. fumiferanae* and *G. fumiferanae* increased after spray treatment in Trapper Creek and also in the check area, Violet Creek, but much more so in Trapper Creek (*table 4*). Parasitism by *A. fumiferanae* was similar in both areas before treatment but was significantly greater in Trapper Creek (99 percent confidence level) than in the check area within 5 days after the mexacarbate application (*table 4*). The following year, however, parasitism by *A. fumiferanae* returned to about its 1966 prespray level and was again similar for both areas (*table 4*).

Prespray parasitism of budworm by *G. fumiferanae* was significantly higher (99 percent confidence level) in Violet Creek than in Trapper Creek (*table 4*). But the increase (significant at the 99 percent confidence level) in parasitism by *G. fumiferanae* following treatment resulted in approximately similar levels of parasitism in the study areas by the 5-day postspray population sample. In 1967, parasitism by *G. fumiferanae* returned to its 1966 prespray level in Trapper Creek, but was lower in Violet Creek (*table 4*).

Parasitism by *P. hariolus* and *Mesochorus* sp. also increased after the mexacarbate treatment in Trapper Creek but not at a significant level (*table 4*). These parasites were attacking large budworm larvae during and after mexacarbate application. Some of these parasites, therefore, were exposed to the insecticide, but there is no evidence that they were affected by it in 1966. Only two *Mesochorus* sp., however, were recovered the following year.

The incidence of tachinids in the budworm populations also increased after treatment in Trapper Creek (95 percent confidence level) and in the check area (99 percent confidence level) (*table 4*). These parasites also were in the midst of their attack period during and after treatment and, therefore, some were exposed to the insecticide. Nevertheless, in contrast to the 1965 studies, we found no difference in parasitism by tachinids between treatment and check areas in 1966 and 1967. Except for the postspray samples from Trapper Creek, the numbers of tachinids reared from budworm larvae from the two areas were similar (*table 4*).

The 1968 Tests

Mexacarbate applied at the rate of 1 oz a.i./pt/acre (28.35 g a.i./473.16 ml/0.404 ha) reduced budworm populations about 71 percent in Belmont Creek and 53 percent in Chamberlain Creek (*table 5*). Budworm populations in a check area declined only about 34 percent during the treatment period (*table 5*). These treatments were considered failures because they did not succeed in adequately suppressing budworm population; i.e., treatments did not achieve at least 90 percent mortality. A review of the decisions and events that occurred before and during these tests suggests that mexacarbate was applied in marginal dosage, and in inadequate volume and application for maximum area coverage and field effectiveness in the 1968 tests.

The 1965 and 1966 field tests of mexacarbate showed that mexacarbate applied at the rate of 0.15 lb a.i. (2.4 ounces)/acre, (68.04 g a.i./0.404 ha) can effectively suppress budworm populations. Laboratory tests have indicated that mexacarbate will cause 90 percent mortality of 5th and 6th instars at approximately 0.49 to 0.74 oz/acre (13.9 to 21.0 g/0.404 ha) (Robertson and others 1976). There is a strong possibility that the dosage of 1 oz a.i./acre (28.35 g a.i./0.404 ha) was marginal for killing large budworm larvae. Laboratory tests also showed the LD_{90} dosage required to kill mature 6th instars (body weight > 110 mg) ranged from 1.9 to 11 oz/acre (53.9 to 311.9 g/0.404 ha). The strong statistical difference between the LD_{90} dosages for small and mature 6th instars emphasizes the importance of timing spray applications before mature 6th instar larvae appear in the population (Robertson and others 1976).

Also, a given amount of mexacarbate applied at 1 gal formulation per acre (3.785 l/0.404 ha) would normally result in better coverage of target areas than an equal amount of mexacarbate applied at 1 pt formulation per acre (0.47 l/0.404 ha) because of the greater volume being applied. Kromekote cards used in the 1965 and 1966 tests to trace dispersion of the nonaerosal portion of the insecticide in the target areas showed an average of 50.38 ± 34.70 (95 percent probability level) spray droplets (those $> 50\mu$) per square centimeter for the 1966 test. Given the areal coverage problems of aerial application of insecticides, a pint per acre would produce a substantially lower spray droplet density average than would 1 gallon per acre.

Table 4—*Estimates of parasitism of western spruce budworm (Choristoneura occidentalis Freeman) populations by the five most numerous parasites, and number of parasites reared from collections of the host insect, before and after mexacarbate treatments in 1966 and 1967*

Study area and treatment	1966				1967	
	Prespray estimate[1]	Parasites reared	Postspray estimate[1]	Parasites reared	Estimate[1] (1 year)	Parasites reared
			Apanteles fumiferanae			
Trapper Creek (Mexacarbate)	2.15 [2](0.29)	79	[3]14.47 (2.61)	34	1.24 (0.47)	7
Violet Creek (Check)	3.10 (0.47)	53	6.16 (1.11)	53	2.23 (0.75)	9
			Glypta fumiferanae			
Trapper Creek (Mexacarbate)	3.49 (0.41)	128	[3]20.00 (3.05)	47	3.72 (0.87)	21
Violet Creek (Check)	[4]9.75 (0.96)	167	[5]15.93 (1.59)	137	4.95 (1.09)	20
			Phaeogenes hariolus			
Trapper Creek (Mexacarbate)	0.16 (0.08)	6	2.13 (0.93)	5	— —	—
Violet Creek (Check)	— —	—	0.93 (0.32)	8	— —	—
			Mesochorus sp.			
Trapper Creek (Mexacarbate)	0.05 (0.04)	2	1.70 (0.98)	4	0.35 (0.25)	2
Violet Creek (Check)	0.06 (0.06)	1	0.47 (0.23)	4	— —	—
			Tachinids			
Trapper Creek (Mexacarbate)	1.34 (0.23)	49	[5]6.38 (1.91)	15	0.71 (0.34)	4
Violet Creek (Check)	2.75 (0.58)	47	[3]9.65 (1.46)	83	0.74 (0.41)	3

[1] Parasitism is expressed as the number of parasites per 100 budworm *(C. occidentalis).*

[2] Values in parentheses are standard errors (SE).

[3] Significantly different from the prespray estimate at the 99 percent confidence level, according to t-tests.

[4] Significantly different from the prespray estimate of Trapper Creek at the 99 percent confidence level, according to t-tests.

[5] Significantly different from the prespray estimate at the 95 percent confidence level, according to t-tests.

Table 5—*Trees sampled and estimates of western spruce budworm (Choristoneura occidentalis Freeman) populations at the large larval stage before and after 1968 mexacarbate treatments, percent mortality following treatments, and 1969 and 1970 population estimates*

		1968			1969	1970
Study area	Trees	Prespray estimate[1]	Postspray estimate[1]	Mortality	Estimate (1 year)	Estimate (2 years)
				Percent		
Belmont	40	37.66 [2](34.98)	10.67 (9.95)	71.66 (26.88)	22.40 (1.77)	[3]37.62 (1.91)
Chamberlain	40	54.99 (38.24)	25.81 (18.34)	53.06 (53.24)	31.05 (2.77)	[4]44.65 (2.67)
Check	40	24.06 (26.95)	15.87 (15.34)	34.04 (58.12)	— —	— —

[1] Number of western spruce budworm (*C. occidentalis*) per 1000 square inches (6451.6 square cm) branch surface area.

[2] Values in parentheses are standard errors (SE).

[3] Significant difference compared to preceding sampling period at 99 percent level of confidence.

[4] Significant difference compared to preceding sampling period at 95 percent level of confidence.

In addition, a new aerial technique, applying the concept of atmospheric transport and diffusion of insecticide spray droplets, was used in the 1968 tests. Instead of the sequential swathing technique used in the earlier tests, these applications were made along ridges and were tailored to use the normal air patterns existing in the test drainages to transport the small spray droplets throughout the forest. A weather front moved through the area just before spray application and affected local air drainage patterns. By applying a technique based on conditions that existed before the passage of the weather front, we did not achieve the desired coverage under the new conditions.

Spray dispersion and droplet densities were not measured in treatment areas, because the 1966 tests showed that Kromekote cards could not clearly show spray droplets smaller than 50μ, the more effective portion of the droplet spectrum (Himel and Moore 1967). We had no way, therefore, to determine the dispersion of any part of the droplet spectrum. Observations made in Chamberlain during treatment indicated that the small droplets never reached understory trees (15 to 20 ft [4.6 to 6.1 m] high). Many live larvae were found on trees throughout the area in late afternoon after treatment and during the postspray sample.

In 1969, budworm populations on the check area declined beyond the capabilities of our sampling effort to detect them. The area was not reexamined in 1970. Budworm populations on the treated areas were moderately high in 1969, and increased significantly in 1970 (*table 5*).

PARASITISM IN THE 1968 TESTS

Although the 1968 treatments did not achieve the degree of suppression of the budworm population desired, they did provide some unexpected information on parasites. Parasitism of budworm populations by all groups of parasites tended to increase during and after treatments in all areas but this increase was significant only in Chamberlain. The total number of parasites reared from the postspray budworm collections far exceeded the number reared from the prespray collections. This situation was especially pronounced in the Chamberlain area which had only 53 percent larval mortality from mexacarbate treatments compared with the Belmont area which had about 71 percent larval mortality.

The overwintering parasites, *G. fumiferanae* and *A. fumiferanae,* and the late larval, pupal parasites—the tachinids—were mainly responsible for the significant increase in parasitism of budworm populations in Chamberlain sampled 4 days after treatments (*table 6*). Parasitism by *A. fumiferanae* increased significantly (at the 95 percent confidence level) in Chamberlain within 4 days after treatment and remained significantly higher than the pretreatment level for the following 2 years. Parasitism by *G. fumiferanae* remained significantly higher than the pretreatment level for 1 year and returned to the pretreatment level in 1970 (*table 6*). Tachinids and *Mesochorus* sp. were attacking budworm larvae at the time mexacarbate was applied. Parasitism by tachinids increased significantly immediately after treatment, but declined to pretreatment levels the following year (*table 6*).

The large number of parasites reared during the 4-day postspray sample in Chamberlain was particularly noteworthy (*table 6*). Apparently the relatively high survival of budworm from the mexacarbate treatment in Chamberlain (47 percent survival), relative to Belmont (29 percent survival), also resulted in a disproportionately higher survival of parasitized larvae in Chamberlain. The studies of mexacarbate treatment on budworm reported here and earlier (Williams and others 1969) and of other insecticide treatments on spruce budworm, *Choristoneura fumiferanae* (Clem.) populations (MacDonald 1959) have shown an increase in parasitism of budworm surviving insecticide treatments. This increase may be explained by the lower exposure of the relatively inactive, moribund parasitized larvae to random mortality factors, such as insecticide spray droplets, resulting in a higher proportionate survival of parasitized larvae over healthy, active nonparasitized larvae.

Table 6—*Estimates of parasitism of western spruce budworm (Choristoneura occidentalis Freeman) populations by the four most numerous parasites, and number of parasites reared from collections of the host insect, before and after 1968 mexacarbate treatments, and for 2 years following in the study areas*

Study area	1968				1969		1970	
	Prespray estimate[1]	Parasites reared	Postspray estimate[1]	Parasites reared	Estimate[1] (1 year)	Parasites reared	Estimate[1] (2 years)	Parasites reared
	Apanteles fumiferanae							
Belmont	5.47[2] (0.93)	49	6.61 (0.79)	79	6.61 (1.02)	83	7.27 (1.39)	85
Chamberlain	3.28 (0.44)	43	[3]6.14 (0.71)	221	[3]6.24 (0.75)	175	[3]8.88 (0.79)	152
Check	4.49 (0.89)	35	5.83 (0.78)	95	— —	—	— —	—
	Glypta fumiferanae							
Belmont	11.84 (1.77)	106	14.21 (1.68)	170	10.43 (1.13)	131	5.22 (0.79)	61
Chamberlain	7.56 (0.87)	99	[3]13.94 (1.04)	502	[3]11.81 (0.73)	331	6.78 (0.91)	116
Check	5.90 (0.82)	46	9.69 (1.15)	158	— —	—	— —	—
	Tachinids							
Belmont	0.78 (0.29)	7	2.09 (0.67)	25	0.32 (0.16)	4	0.17 (0.12)	2
Chamberlain	0.92 (0.29)	12	[3]2.94 (0.48)	106	0.43 (0.15)	12	0.29 (0.15)	5
Check	— —	—	0.18 (0.10)	3	— —	—	— —	—
	Mesochorus sp.							
Belmont	0.22 (0.22)	2	0.84 (0.37)	10	0.24 (0.14)	2	0.09 (0.08)	1
Chamberlain	0.08 (0.08)	1	0.19 (0.07)	7	0.29 (0.13)	8	0.06 (0.06)	1
Check	0.26 (0.24)	2	0.55 (0.28)	9	— —	—	— —	—

[1] Parasitism is expressed as the number of parasites per 100 budworm (*C. occidentalis*).

[2] Values in parentheses are standard errors (SE).

[3] Significantly different from the prespray level at the 95 percent confidence level.

We believe the above explanation is particularly pertinent for budworm larvae parasitized by *A. fumiferanae* and *G. fumiferanae*. These parasites attack the 1st and 2nd instars and, except for some early emergence of *A. fumiferanae* from the 4th instar, their progeny emerge from 5th and 6th instars. A parasitized 5th-6th instar budworm containing a fully developed parasite about to emerge is usually inactive and moribund. These larvae probably would not be as exposed to insecticide droplets and residues as normal, highly mobile, actively feeding 5th-6th instars. The insecticide treatments were applied at the time most of the budworm populations were in 5th and 6th instars.

Because tachinids and other late larval, pupal parasites attacked budworm during and after treatments, high proportionate survival of parasitized larvae does not explain the increase in parasitism of budworm by these parasites. We would not expect newly parasitized budworm larvae to be as inactive and moribund as those containing the fully developed larvae of *A. fumiferanae* and *G. fumiferanae*. The exposure of newly parasitized budworm, therefore, should be similar to that of healthy nonparasitized budworm larvae. Parasitization of budworm larvae after treatment probably contributed substantially to the increase in parasitism by late larval, pupal parasites.

Our studies suggest that high proportionate survival of parasitized larvae, in terms of percentage of the total host population of budworm larvae and in actual numbers of surviving parasites, results when an insecticide kills a relatively low percentage of the host population. As more and more of the total budworm larval population is killed by the insecticide, increasing numbers of parasitized budworm larvae are also killed. This situation results in a still higher proportionate survival of parasitized larvae, relative to nonparasitized larvae, but lower numbers of parasitized larvae survive. We observed lower survival of parasitized larvae in the 1965 and 1966 tests in which over 90 percent of the budworm populations were killed.

In the 1968 studies, however, large numbers of parasitized budworm larvae survived treatments. As a result, a substantial increase occurred in he numbers of parasites (*A. fumiferanae, G. umiferanae*, and tachinids) reared from posttreatment collections of budworm larvae, particularly hose from Chamberlain in 1968, compared to hose reared in the 1965 and 1966 studies (*table 6*). Consequently, large numbers of parasites were available in Chamberlain during the summer of 1968 to attack the next generation of budworm larvae. We believe that this situation was responsible for maintaining the high incidence of parasitism by *G. fumiferanae* and *A. fumiferanae* for 1 and 2 years in posttreatment budworm populations in Chamberlain. Furthermore, we believe that high parasite survival is due directly to the relatively low insecticide-induced mortality of budworm larvae obtained in the 1968 tests, compared to the high mortality obtained in the 1965 and 1966 tests.

Bartlett (1963), in discussing guidelines in development of integrated programs, suggests that any differential toxicity response to the insecticide favoring the natural enemy over the pest, can usually be accentuated by a decrease in the field dosage to a point where somewhat less than 100 percent of the pest is destroyed. Field data from all parasite studies of mexacarbate treatments on western spruce budworm populations reported here support this statement. More specifically, results from the 1968 treatments suggest that parasite survival is enhanced even more under insecticide treatments when less than 70 percent of the host insect is destroyed. In this situation, a large reservoir of parasites is available to parasitize the host insect the following year. These 1968 treatment results in the Chamberlain area further suggest that parasitism and parasite abundance may even be increased for a few years as a result of insecticide treatment.

Reports of various pesticide programs for control of agricultural insect pests have frequently described the virtual elimination of the natural enemies of the pests, followed by a resurgence of the pest populations—often to higher levels than before pesticide treatments (Van den Bosch 1970, Kilgore and Doutt 1967, and Pickett and MacPhee 1965). Studies of the effects of pesticides on forest insects, mainly the spruce budworm and its parasites, however, have shown severe suppression of host populations and increased parasitism after treatment.

One of the first studies reporting high proportionate survival of parasitized budworm larvae (Eaton and others 1949) mentioned that 70 percent of the surviving budworm from the plots near Heppner, Oregon, treated with DDT in 1948, were small parasitized larvae that escaped the spray probably through failure to travel and feed. An unpublished report on the effects of DDT applied in 1949 and 1950 to budworm-infested forests in Washington and Oregon concluded that *Campoplex* sp. and the two overwintering parasites, *A. fumiferanae* and *G. fumiferanae*, survived aerial sprays of DDT in sufficient numbers to exert even greater natural control of the budworm than before spraying.[4]

Studies in Eastern Canada on the effects of DDT on spruce budworm *Choristoneura fumiferanae* (Clemens) and its two overwintering parasites in New Brunswick described a distinct tendency toward increased parasitism by *A. fumiferanae* and decreasing parasitism by *G. fumiferanae* in succeeding postspray budworm generations (MacDonald 1959). These are the only parasites present in the 3rd and 4th instars, the budworm stages when spraying commences in Canada and, therefore, are the parasites most vulnerable to the insecticides. Higher proportionate survival of *A. fumiferanae* parasitized budworm and earlier emergence of *A. fumiferanae* from the hosts, in many cases before spraying, were the major reasons given for differences in parasitism between the parasites (MacDonald 1959).

Another series of studies on the effects of DDT applied in 1958 against the budworm in eastern Oregon reported good survival of *A. fumiferanae* and, to a lesser extent, *G. fumiferanae,* reared from survivors collected 10 or 11 days after spraying. Parasitism of small larvae 1 year after spraying was 7 to 14 percent higher than that in spring before spraying (Carolin and Coulter 1971). None of the common parasites which attack full-grown larvae, however, were reared from surviving budworm. Parasitism of these larvae increased dramatically the following year on some of the plots (Carolin and Coulter 1971).

Leonard and Simmons (1974) reported on the immediate effects of mexacarbate on the parasites of spruce budworm, *C. fumiferanae* (Clemens) in Aroostock County, Maine. Their data showed that pupal parasites—tachinids and *Ephialtes ontario* Cresson—were significantly lower i mexacarbate-treated areas than in untreated area during the year of application. This differenc indicates that mexacarbate applied when most o the budworm are 5th (of 6) instars may ki some adult parasites attacking late-stage budworm larvae and pupae. Pupal parasites that star attacking the late-stage larval instars a day o two after application of mexacarbate, howeve would not be affected by this insecticide becaus its residual life is short, less than 2 days (Robertson and others 1976).

Adults of *A. fumiferanae* and *G. fumiferana* are not normally exposed to spraying operation because their presence is synchronized with that o budworm moths, eggs, and the first and possibly the second budworm instar in hibernacula (Blais 1977). Larvae of these parasites, however are exposed to insecticides applied against 5th an 6th instar budworm in several ways. We woul expect some who are still in budworm larvae tha came in contact with lethal amounts of the insecticide to be killed. Our parasite rearings indicate that sublethal amounts of the insecticides to parasitized budworm larvae may have adversely affected emerging parasites, because a number o them had spun their cocoons and died. We ha expected some of those who emerged durin treatment to be killed, and the danger of exposur following treatment related to the residual lif of the insecticide.

The exposure of the late larval, pupal parasites, e.g., *P. hariolus, Mesochorus* sp. and the tachinids, to insecticides applied against 5th and 6t instars of the budworm, is different from tha of parasites that attack the young or early budworm instars. Adult late-larval parasites wer flying and attacking budworm larvae before, during, and after treatment. Some of the adult parasites exposed to the treatments were killed. We found some evidence of this mortality i 1965 by the numbers of tachinids collected i drop cloths, and the number reared from th 1965 post-treatment collections of budworm larvae. The danger of exposure after treatment to the adult parasite and eventually to its progeny would be related to the residual life or persistence of the insecticide.

---

[4] W. K. Coulter. *Effects of aerial spraying upon parasites of the spruce budworm.* Talk given at Second Annual Meeting, Pacific Branch, Entomol. Soc. Amer., Bend, Oreg. June 22-24, 1954.

CONCLUSIONS

Aerially applied mexacarbate to 5th and 6th instars of western spruce budworm effectively controlled this insect pest to the extent of ≥ 90 percent mortality when the insecticide was applied at the rate of 0.15 lb a.i./gal/acre (68.04 g a.i./ 3.785 1/0.404 ha.). Mexacarbate applied aerially at the rate of 1 oz a.i./pt/acre (28.35 g a.i./473.16 ml/0.404 ha) reduced budworm populations (50 to 70 percent mortality) but treatments were considered failures because mortality of the budworm was < 90 percent. This latter dosage was successful, however, in that higher parasite survival provided unexpected information on several common parasites of the western spruce budworm.

The results of our studies suggest that parasite survival may be enhanced under conditions of moderate suppression of 5th and 6th instar budworm populations (50 to 70 percent mortality) by mexacarbate. A large reservoir of parasites is available to attack budworm larvae of the succeeding generation. And increased parasitism under these conditions may last for several years. These phenomena merit further investigation because they indicate compatible roles for insecticides and parasites in the control of budworm populations. Possibly nonpersistent insecticides can be used not only to reduce directly epidemic budworm populations, but also to increase the ratio of parasites to budworm, thereby enhancing parasite effectiveness in controlling budworm for several years after chemical treatment.

LITERATURE CITED

Bartlett, Blair R.
1963. **The contact toxicity of some pesticide residues to Hymenopterous parasites and cocinellid predators.** J. Econ. Entomol. 56(5):694-698.

Blais, J. R.
1977. **Effects of aerial application of chemical insecticides on spruce budworm parasites.** Can. For. Serv. Bimonthly Res. Notes 33(6):41-42.

Buffam, P.E., H.E. Meyer, and R.P. Miskus.
1967. **Small-scale trials of five insecticides...sprayed on spruce budworm in Montana.** USDA Forest Serv. Res. Note PSW-159, 4 p. Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif.

Carolin, V. M., and W. K. Coulter
1971. **Trends of western spruce budworm and associated insects in Pacific Northwest forests sprayed with DDT.** J. Econ. Entomol. 64(1):291-297.

Eaton, C.B., J.A. Beal, R.L. Furniss, and C.F. Speers
1949. **Airplane and helicopter spraying with DDT for spruce budworm control.** J. For. 47:823-827.

Freeman, T. N.
1967. **On coniferophagous species of *Choristoneura* (Lepidoptera: Tortricidae) in North America. I.** Some new forms of *Choristoneura* allied to *C. fumiferanae*. Can. Entomol. 99:449-455.

Graham, Richards J., and William R. Gould
1967. **Effects of Zectran on aquatic organisms in trout streams of western Montana.** Special Report. USDA Fish and Wildl. Serv., Bur. Sport Fish. and Wildl. Div. of Fish. Serv. Portland, Oreg., 23 p., illus.

Himel, C. M.
1969a. **The fluorescent particle spray droplet tracer method.** J. Econ. Entomol. 62(4)912-916.

Himel, C. M.
1969b. **The optimum size for insecticide spray droplets.** J. Econ. Entomol. 62(4):919-925.

Himel, C. M., and A. D. Moore
1969. **Spray droplet size in the control of spruce budworm, bollweevil, bollworm, and cabbage looper.** J. Econ. Entomol. 62(4):916-918.

Himel, Chester M., and Arthur D. Moore
1967.**Spruce budworm mortality as a function of aerial spray droplet size.** Science 156(3779):1250-1251.

Honing, Frederick W.
1968. **Spruce budworm Zectran pilot control test, Bitterroot National Forest. 1966.** USDA Forest Serv. Northern Reg. Div. State and Priv. For. Missoula, Mont., 12 p., illus.

Kilgore, W. V., and R. L. Doutt
1967. **Pest control, biological, physical and selected chemical methods.** 477 p. Academic Press, New York and London.

Leonard, D. E., and G. A. Simmons
1974. **The effects of Zectran on the parasitoids of the spruce budworm, *Choristoneura fumiferanae* (Lepidoptera: Tortricidae).** Can. Entomol. 106:545-554.

Lyon, Robert L.
1976. **The status of chemicals for suppression of spruce budworm in the United States.** *In* Proceedings of a symposium on the spruce budworm [Nov. 11-14, 1974. Alexandria, Va.] p. 91-96. USDA Forest Serv. Misc. Publ. 1327., 188 p., illus.

Lyon, R. L., C. E. Richmond, J. L. Robertson, and B. A. Lucas
1972. **Rearing diapause and diapause-free western spruce budworm (*Choristoneura occidentalis* (Lepidoptera: Tortricidae)) on an artificial diet.** Can Entomol. 104:417-426.

MacDonald, D.R.
1959. **Biological assessment of aerial forest spraying against spruce budworm in New Brunswick. III. Effects on two over-wintering parasites.** Can. Entomol. 91:330-336.

McGregor, Mark D., and Jerald E. Dewey

1968. **Zectran pilot test to control spruce budworm in Belmont and Chamberlain Creeks, Blackfoot River drainage, Montana.** USDA Forest Serv. Northern Reg., Div. State and Priv. For., Missoula, Mont., 11 p., illus.

Mussehl, Thomas W., and Philip Schlandweiler

1969. **Forest grouse and experimental spruce budworm insecticide studies.** Montana Fish and Game Dep. Tech. Bull. 4, p. 1-53.

Parker, J. Louise

1967. **Aerosols for forest spraying.** *In* What's new in research, May 19, 1967, p. 1-2, illus. USDA Forest Serv. Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif.

Pickett, A. D., and A. W. MacPhee

1965. **Twenty years experience with integrated control programs in Nova Scotia apple orchards.** 12th Int. Congr. Entomol. Proc. London, 597 p.

Pillmore, R.E., E.L. Flickinger, and M.L. Richmond

1971. **Forest spraying of Zectran and its safety to wildlife.** J. For. 69(10): 721-727.

Randall, A. P.

1976. **Insecticides, formulations, and aerial applications technology for spruce budworm control.** *In* Proceedings of a symposium on the spruce budworm [Nov. 11-14, 1974. Alexandria, Va.]. p. 77-90. USDA Forest Serv. Misc. Publ. 1327, 188 p., illus.

Robertson, Jacqueline, Nancy Gillette, Melvin Look, Barbara Lucas, and Robert L. Lyon

1976. **Toxicity of selected insecticides applied to western spruce budworm.** J. Econ. Entomol. 69(1):99-104.

U.S. Forest Service

1972. **Nitrogen-pressurized spray system for C-47 airplanes.** Equip. Dev. and Test Rep. 3400/5200-1, 12 p., illus. USDA Forest Serv. Equip. Dev. Cent. Missoula, Mont.

Van den Bosch, R

1970. **Pesticides: Prescribing for the ecosystem.** Environment 12(3):20-25, illus.

Williams, Carroll B. Jr., and Gerald S. Walton

1968. **Effects of naled and Zectran on the budworm, *Choristoneura occidentalis*, and associated insects in Montana.** J. Econ. Entomol. 61(3):784-787.

Williams, Carroll B., Jr., Gerald S. Walton, and Charles F. Tiernan

1969. **Zectran and naled affect incidence of parasitism of the budworm, *Choristoneura occidentalis* in Montana.** J. Econ. Entomol. 62(2):310-312.

Wilson, F. F., and J. L. Bean

1964. **A field key to the adult *Hymenopterous* parasites of the spruce budworm in Minnesota.** USDA Forest Serv. Res. Note LS-53, 4 p. Lake States Forest Exp. Stn., St. Paul, Minn.

Dep. Agric., Berkeley, Calif.

In tests on the Bitterroot National Forest, Montana, in 1965 and 1966, mexacarbate, aerially applied at the rate of 0.15 lb a.i./gal/acre (68.04 g a.i./3.785 1/0.404 ha), killed about 90 percent of the western spruce budworm (*Choristoneura occidentalis* Freeman) populations. More parasitized budworm larvae survived treatments than nonparasitized. *Apanteles fumiferanae* Viereck and *Glypta fumiferanae* Viereck—two overwintering parasites—and *Phaeogenes hariolus* (Cresson), *Mesochorus* sp., and tachinids—late larval, pupal parasites—increased following treatments. But parasites tended to return to pretreatment levels the next year. In 1968, mexacarbate, aerially applied at the rate of 1 oz a.i./pt/acre (28.35 g a.i./473.16 ml/0.404 ha), achieved 71 percent mortality in one area and 53 percent in another. *A. fumiferanae, G. fumiferanae,* and tachinids increased in the area of lowest budworm mortality, and parasitism by *A. fumiferanae* and *G. fumiferanae* remained significantly higher than the 1968 prespray level for from 1 to 2 years, respectively. The results suggest that mexacarbate may be used to moderately suppress populations of budworm larvae in order to increase the ratio of parasites to budworm.

Retrieval Terms: Insecticides; mexacarbate; naled; *Choristoneura occidentalis; Apanteles fumiferanae; Glypta fumiferanae; Phaeogenes hariolus; Mesochorus;* tachinids.

Williams, Carroll B., Jr., Patrick J. Shea, and Mark D. McGregor.
1979. **Effects of aerially applied mexacarbate on western spruce budworm larvae and their parasites in Montana.** Res. Paper PSW-144, 14 p. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

In tests on the Bitterroot National Forest, Montana, in 1965 and 1966, mexacarbate, aerially applied at the rate of 0.15 lb a.i./gal/acre (68.04 g a.i./3.785 1/0.404 ha), killed about 90 percent of the western spruce budworm (*Choristoneura occidentalis* Freeman) populations. More parasitized budworm larvae survived treatments than nonparasitized. *Apanteles fumiferanae* Viereck and *Glypta fumiferanae* Viereck—two overwintering parasites—and *Phaeogenes hariolus* (Cresson), *Mesochorus* sp., and tachinids—late larval, pupal parasites—increased following treatments. But parasites tended to return to pretreatment levels the next year. In 1968, mexacarbate, aerially applied at the rate of 1 oz a.i./pt/acre (28.35 g a.i./473.16 ml/0.404 ha), achieved 71 percent mortality in one area and 53 percent in another. *A. fumiferanae, G. fumiferanae,* and tachinids increased in the area of lowest budworm mortality, and parasitism by *A. fumiferanae* and *G. fumiferanae* remained significantly higher than the 1968 prespray level for from 1 to 2 years, respectively. The results suggest that mexacarbate may be used to moderately suppress populations of budworm larvae in order to increase the ratio of parasites to budworm.

Retrieval Terms: Insecticides; mexacarbate; naled; *Choristoneura occidentalis; Apanteles fumiferanae; Glypta fumiferanae; Phaeogenes hariolus; Mesochorus;* tachinids.

Dep. Agric., Berkeley, Calif.

In tests on the Bitterroot National Forest, Montana, in 1965 and 1966, mexacarbate, aerially applied at the rate of 0.15 lb a.i./gal/acre (68.04 g a.i./3.785 1/0.404 ha), killed about 90 percent of the western spruce budworm (*Choristoneura occidentalis* Freeman) populations. More parasitized budworm larvae survived treatments than nonparasitized. *Apanteles fumiferanae* Viereck and *Glypta fumiferanae* Viereck—two overwintering parasites—and *Phaeogenes hariolus* (Cresson), *Mesochorus* sp., and tachinids—late larval, pupal parasites—increased following treatments. But parasites tended to return to pretreatment levels the next year. In 1968, mexacarbate, aerially applied at the rate of 1 oz a.i./pt/acre (28.35 g a.i./473.16 ml/0.404 ha), achieved 71 percent mortality in one area and 53 percent in another. *A. fumiferanae, G. fumiferanae,* and tachinids increased in the area of lowest budworm mortality, and parasitism by *A. fumiferanae* and *G. fumiferanae* remained significantly higher than the 1968 prespray level for from 1 to 2 years, respectively. The results suggest that mexacarbate may be used to moderately suppress populations of budworm larvae in order to increase the ratio of parasites to budworm.

Retrieval Terms: Insecticides; mexacarbate; naled; *Choristoneura occidentalis; Apanteles fumiferanae; Glypta fumiferanae; Phaeogenes hariolus; Mesochorus;* tachinids.

Williams, Carroll B., Jr., Patrick J. Shea, and Mark D. McGregor.
1979. **Effects of aerially applied mexacarbate on western spruce budworm larvae and their parasites in Montana.** Res. Paper PSW-144, 14 p. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

In tests on the Bitterroot National Forest, Montana, in 1965 and 1966, mexacarbate, aerially applied at the rate of 0.15 lb a.i./gal/acre (68.04 g a.i./3.785 1/0.404 ha), killed about 90 percent of the western spruce budworm (*Choristoneura occidentalis* Freeman) populations. More parasitized budworm larvae survived treatments than nonparasitized. *Apanteles fumiferanae* Viereck and *Glypta fumiferanae* Viereck—two overwintering parasites—and *Phaeogenes hariolus* (Cresson), *Mesochorus* sp., and tachinids—late larval, pupal parasites—increased following treatments. But parasites tended to return to pretreatment levels the next year. In 1968, mexacarbate, aerially applied at the rate of 1 oz a.i./pt/acre (28.35 g a.i./473.16 ml/0.404 ha), achieved 71 percent mortality in one area and 53 percent in another. *A. fumiferanae, G. fumiferanae,* and tachinids increased in the area of lowest budworm mortality, and parasitism by *A. fumiferanae* and *G. fumiferanae* remained significantly higher than the 1968 prespray level for from 1 to 2 years, respectively. The results suggest that mexacarbate may be used to moderately suppress populations of budworm larvae in order to increase the ratio of parasites to budworm.

Retrieval Terms: Insecticides; mexacarbate; naled; *Choristoneura occidentalis; Apanteles fumiferanae; Glypta fumiferanae; Phaeogenes hariolus; Mesochorus;* tachinids.

PACIFIC SOUTHWEST
Forest and Range
Experiment Station

SERVICE
ARTMENT OF AGRICULTURE

Soil Heating in Chaparral Fires: effects on soil properties, plant nutrients, erosion, and runoff

Leonard F. DeBano   Raymond M. Rice   C. Eugene Conrad

CLEMSON UNIVERSITY LIBRARY
SEP 8 1980
SCI., TECH. & AGR. DIV.

RESEARCH PAPER PSW-145

The Authors

LEONARD F. DEBANO was formerly principal soil scientist at the Station, and stationed at Glendora, Calif. He is now in charge of research on management alternatives for Southwest watersheds, Rocky Mountain Forest and Range Experiment Station, stationed at Tempe, Ariz. He earned a B.S degree in range management and forestry at Colorado State University (1955), an M.S. degree in range management at Utah State University (1957), and a doctorate in soil science at the University of California (1966). He joined the Forest Service in 1962. **RAYMOND M. RICE** is in charge of the Station's research unit studying processes affecting management of Pacific coastal forests on unstable lands, with headquarters in Arcata, Calif. He earned a forestry degree at Montana State University (1951), an M.S. degree in forestry at the University of California (1961), and a doctorate at Colorado State University (1970). He joined the Forest Service in 1951 and the Station's research staff in 1956. **C. EUGENE CONRAD** heads the Station's research unit studying the management of chaparral and related ecosystems, with headquarters at Riverside, Calif. He earned a B.S. degree in agriculture (1956) and an M.S. degree in range management and plant ecology (1959) from Oregon State University. He joined the Forest Service and Station's research staff in 1961.

Soil Heating in Chaparral Fires: effects on soil properties, plant nutrients, erosion, and runoff

Leonard F. DeBano Raymond M. Rice C. Eugene Conrad

CONTENTS

Page

Introduction 1
Soil Heating 2
  Nature of Soil Heating 2
  Differences in Heating, by Fire Types 2
  Effects of Soil Water on Heating 4
  Variability of Surface Temperatures 4
  Predictions of Heat Effects 5
Effects of Fire on Chaparral Ecosystems 7
  Soils 7
  Plant Nutrients 11
  Soil Wettability 13
  Infiltration 14
  Runoff and Erosion 15
Conclusions 16
Literature Cited 17
Appendix 20

Pacific Southwest Forest and Range Experiment Station
P.O. Box 245
Berkeley, California 94701

August 1979

IN BRIEF . . .

DeBano, Leonard F., Raymond M. Rice, and C. Eugene Conrad.
1979. **Soil heating in chaparral fires: effects on soil properties, plant nutrients, erosion, and runoff.** Res. Paper PSW-145, 21 p. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.
Retrieval Terms: chaparral; brush fires; soil heating; heat effects.

The Revised Fire Management Policy, adopted by the Forest Service, U.S. Department of Agriculture, in 1977, "encourages land managers to make more use of prescription fire to protect, maintain, and enhance the natural resource values and aesthetics within approved areas on the National Forest." Prescribed fire would be one approach to reducing fuel hazard in chaparral brushlands in southern California. These brushlands burn as often as every 30 years, and resulting fires can threaten urban as well as rural areas.

Prescribed fire would be used to burn small areas of chaparral at different times to create a patchwork of brush stands of varying age. Such a mosaic would pose less of a hazard than would large continuous stands now commonly found throughout southern California. Renewed interest in fuel modification using fire, however, has raised questions of the effects of fire on the environment.

This paper is a state-of-the-art report on what is known about the effects of fire on chaparral in southern California, including effects on soil, plants, micro-organisms, erosion, and hydrology. It summarizes data on soil heating collected by other investigators, and more recent data recorded during prescribed burns and a wildfire in southern California. These data were recorded from 1968 to 1975 by self-contained pyrometers buried on the site being burned. These instruments recorded soil temperatures continuously at 2.5-cm intervals downward in the soil. Among the fires studied, wide differences in soil heating were measured because of variations in fuel loading, weather conditions, and soil-water content.

Soil heating data were summarized, analyzed, and used to construct three stylized temperature curves of soil heating during light, moderate, and intense fires. These stylized curves were used to predict the effects of burning intensity on the physical, chemical, and biological properties of soils. Soil nitrogen losses based on fire intensity were estimated from the stylized curves. Less volatile nutrients were found to be released as highly mobile ions to be metabolized by plants or micro-organisms, or were lost from the site by erosion and runoff. Micro-organisms were affected lethally at much lower temperatures than those necessary to change nonliving organic matter.

Light intensity burns on chaparral brushlands released smaller amounts of plant nutrients and, therefore, smaller erosional losses occurred than after wildfires. Site differences—slope steepness, kind of soil, amount of rainfall—resulted in different rates of erosion. Despite site differences, a higher degree of soil heating during a wildfire would be expected to do more damage than would a cooler, prescribed burn.

Chaparral brushlands in southern California burn as often as every 30 years (Muller and others 1968). Since 1945, the State's Public Resources Code has set forth fuel hazard reduction as a primary goal in the management of public lands.[1] A variety of techniques are available in attempts to reduce fuel hazard. One of these techniques—prescribed burning—has received increasing attention in recent years. The Revised Fire Management Policy adopted by the Forest Service, U.S. Department of Agriculture (1977) "encourages land managers to make more use of prescription fire to protect, maintain, and enhance the natural resource values and aesthetics within approved areas on the National Forest."

In the chaparral areas of southern California, prescribed fire would be used to burn small areas of brushland at different times to create a patchwork of brush stands of varying age. Such a mosaic would pose less of a hazard than would large continuous stands of brush now commonly found throughout southern California. But renewed interest in fuel modification using fire raises questions of the effects of fire on the environment and specifically on how fire affects soils, plants, micro-organisms, erosion, and hydrology.

Information on fire in chaparral areas of California has been collected since the 1930's by several investigators (Bentley and Fenner 1958, Lawrence 1966, Sampson 1944). However, much of this soil heating data presents only the maximum temperatures reached and only a limited amount of continuous temperature data. To supplement this data, we collected additional soil temperature data during several prescribed burns and one wildfire in southern California between 1968 and 1975. Most of the data were collected with recording pyrometers, although tempil tablets were used to measure maximum temperatures on some fires. Only recording pyrometer data are reported in this paper. The recording pyrometers consisted of battery-operated recorders connected to either chromel-alumel or iron-constantan thermocouples. These instruments could measure temperatures up to 1315°C. The recorders were enclosed in an insulated metal box and buried in the soil to prevent damage during the fire. Temperatures were measured at the surface, 2.5 cm, 5.0 cm, and 10 cm in the soil during the earlier studies, but were changed to the surface, 1, 2, and 4 cm in 1970. At some sites, only surface temperatures were measured.

Descriptive information on vegetation and soils was also collected. During the earlier studies done in 1968, only observational data were taken on vegetation and soils because most of our effort was directed toward installing instruments for measuring soil temperatures. By 1973, however, detailed site measurements were taken and, on a prescribed burn at the Paradise Valley site near Santa Maria, California, nutrients in the plants, litter, and soils, along with soil water at several depths, were measured before and after burning (DeBano and Conrad 1978).

A summary table of pertinent vegetation and soils data collected between 1968 and 1975 showing maximum temperatures is provided *(Appendix, table 1)*. Continuous temperature data for some individual fires are given in detail, as necessary, to illustrate the effect of vegetation pretreatment, soil water, or other environmental parameters on soil heating. Data on differences in soil heating during wildfires and prescribed burns are also discussed. Finally, these data were summarized and used to produce stylized soil heating curves which represent light, moderate, and intense burning intensities.

The stylized heating curves were used along with published information to estimate: (1) the direct effects of fire on plants, litter, and soil; and (2) the long-term effects on erosion, surface runoff, and hydrology. As such, this paper constitutes a state-of-the-art report on what is known about fire and its effects on the chaparral environment in southern California.

---

[1] Public Resources Code Section 4491-94, 1945.

Nature of Soil Heating

Soil heating and fire temperatures vary widely among fires and within any particular fire. Maximum temperatures at the surface and downward differ from site to site within a fire and also between fires *(Appendix, table 1)*. Large temperature gradients develop between the surface and underlying soil layers because soil is a poor conductor of heat and only a small portion of the energy released during burning is transferred downward into the soil (DeBano 1974).

Although maximum temperatures can be measured easily and inexpensively, they do not adequately characterize the dynamic relationship between time and temperature—heat pulses—as they develop in litter and soil during a fire. Separate fires may have similar maximum temperatures but different durations of heating. The duration of soil heating is important because it affects the degree of change in soil properties. Heating of longer duration is more damaging than is heating of shorter duration. Longer heating destroys more organic matter and this affects many physical and chemical soil properties. Of particular importance is the effect of soil heating on nitrogen and soil microorganisms contained in the litter and soil.

The effects of different durations of heating are illustrated by a fire at Lone Pine Canyon *(Appendix, table 1)* which had the same maximum temperatures (716°C) at Sites 4 and 6, but the duration of heating was shorter at Site 4 *(fig. 1)* than at Site 6 *(fig. 2)*. The different durations of surface heating were reflected in the maximum temperatures of the 2.5-cm and 5.0-cm soil layers. At the 2.5-cm depth, the temperature on Site 6 was 124°C as compared to 91°C on Site 4. At the 5.0-cm depth, slightly more soil heating was apparent on Site 6 than on Site 4 *(Appendix, table 1)*.

The nature of soil heating with its variations between fires and within a fire, its temperature gradients, heat pulses, and duration is such that the kinetics of fire must be understood if we are to assess accurately the effects of soil heating.

Differences in Heating, by Fire Types

Soil Temperatures During Wildfires and Prescribed Burns

Soil heating during wildfires and prescribed burns may not differ substantially if the soil is dry, large accumulations of dead flammable fuel are present, or the climatic conditions (humidity, air temperatures, and wind) are conducive to rapid burning. The di
ferences between prescribed burning and wildfires a
not as great in chaparral as in forests. In chaparral, t
brush canopy is generally consumed and fire may bu
briskly even at the lower intensities when continuo
spread occurs. This type of fire behavior is consi
erably different than that during prescribed burns
forests where the fire moves through the litter lay
without damaging the overstory of tree canopies. Fi
behavior during chaparral fires can vary widely a
produce large differences in soil heating *(Appendi
table 1)*. These differences must be considered by lan
managers, if the effects of prescribed fires on t
chaparral ecosystem are to be minimized.

Although our information on wildfires is limited, t
one wildfire measured (Lone Pine Canyon, *Appendi
table 1*) showed that maximum temperatures in litt
and soil vary widely. On six sites studied during th
wildfire, maximum temperatures measured in the a
ternoon (Sites 1, 4, 5, and 6) were much higher an

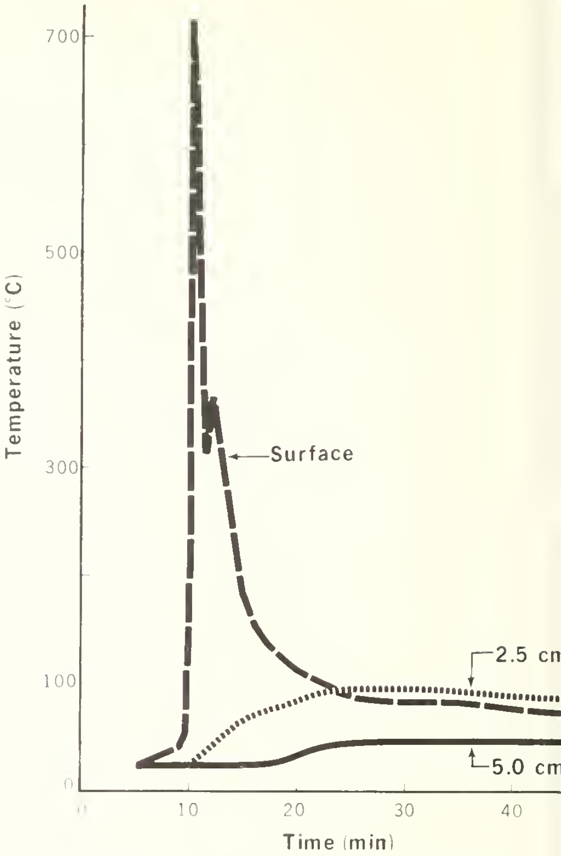


Figure 1—A short duration of heating in the soil and at the s
surface on Site 4 during the Lone Pine Canyon fire in southe
California, September, 1968.

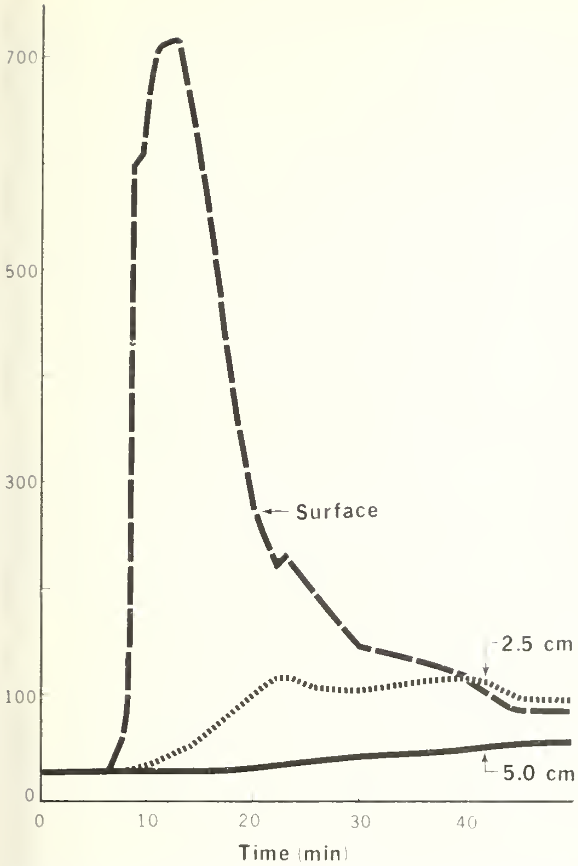


Figure 2—A long duration heat pulse in the soil and at the soil surface on Site 6 during the Lone Pine Canyon fire in southern California, September, 1968.

burning was more severe than during late evening (Sites 2 and 3) *(Appendix, table 1)*. Although meteorological measurements during this wildfire were not available, humidities were lower and burning conditions better during the afternoon compared to the evening. Soil heating during wildfires over larger areas is probably much more severe than during prescribed burning. Uncontrollable wildfires occur when weather conditions are optimum for burning and may sweep over large areas in a short time. Most of the area is burned under conditions of high-fire intensity. Maximum temperatures in the soil and litter during these extreme burning conditions are probably represented by those measured at Lone Pine Canyon on Sites 1, 4, 5, and 6. At Sites 4 and 6, the maximum surface temperature was 716°C, and at Site 5, the 2.5-cm soil layer reached 174°C. Prescribed burning—by design—is carried out under marginal burning conditions. Soil heating is less severe and is probably represented by some of the maximum temperatures measured during the prescribed burns at Mission Viejo. During this fire, surface temperatures at the six sites measured never exceeded 538°C. The temperatures generated during the late evening at Lone Pine Canyon (Sites 2 and 3) were cooler, and correspond to those produced during a prescribed burn of lower intensity.

High maximum temperatures were recorded at other prescribed burn sites, further illustrating the narrow margin between prescribed burning and wildfires. The highest maximum temperatures of any fires studied were recorded during an experimental burn on Site 2 at North Mountain *(Appendix, table 1)* (Dunn and others 1977). Heavy, dry, dead fuel, desiccated prior to the fire, was present on this experimental site and contributed to the severe fire behavior (Green 1970). At Cameron and Palomar, where standing brush was present, fires were also intense *(Appendix, table 1)*.

Although large differences in soil and litter temperatures may not exist between prescribed burns and wildfires, it is possible to predict that some of the conditions will produce less severe fire behavior and thereby minimize soil heating and damage. Burning over a wet or moist soil undoubtedly reduces the impact of fire on litter and soil. Under moist conditons, the canopy may burn briskly with a minimum of heating in the underlying litter and soil.

Prescribed Burns in Chaparral and in Forests

Although considerable data are available on temperatures developed at the surface and in the soil during prescribed fires in forested areas, these data are not useful for predicting soil temperatures during chaparral fires. Soil heating is different during a prescribed fire in chaparral than in a forest in the following ways:

Chaparral	*Forests*
• Flames move through canopy where they destroy variable amounts of the standing vegetation.	• Fires are designed to minimize damage to the larger standing trees (Biswell 1975).
• Fire will burn only under dry conditions because live fuels are consumed during burning.	• Burn is done under moist conditions because dead fuels are the only components burned.
• A thinner litter layer does not insulate the soil against heat radiated downward during a fire.	• A thick layer of duff and litter offer good insulation against heat radiated downward during a fire.
• Temperatures at the soil surface and in the soil are generally higher than those in forests.	• Temperatures at the soil surface and in the soil are generally lower than those in chaparral.

Chaparral Fires

Information on flame temperatures during chaparral fires is scant, and the only data reported has been on a prescribed burn in mixed chaparral (Green 1970). During this burn, the brush was dry and desiccated, and flame temperatures, measured 188 cm above the soil surface, reached 677°C before going off scale on a recording instrument (Green 1970). Green (1970) speculated the flame temperatures on this fire may have reached 1093°C, a level reported earlier by Countryman (1964) in burning piles of brush and trees.

Soil heating during wildfires in chaparral has not been previously measured although soil temperature data has been collected during several prescribed burns. In one such study, Lawrence (1966) studied the ecology of vertebrate animals during fire and reported surface temperatures in dry humus and grass, under a dead log at 5 cm in the soil, and 15 cm in a rodent burrow. Surface temperatures beneath the burning log were highest, reaching a maximum temperature of 560°C and remaining at 482°C for over an hour. The maximum temperature at 5 cm in the soil was 69°C, and was reached during the first 50 minutes of burning. The maximum temperature at 15 cm in the rodent burrow was 72°C. Sampson (1944) measured temperatures under 1.3 cm of litter, 1.9 cm of soil, and 3.8 cm of soil during several controlled burns on chaparral areas in northern California. Maximum temperatures in the top 1.3 cm of soil varied widely from a high of 649°C under chamise litter, to a low of 97°C at the same depth under a wedgeleaf ceanothus with scattered grasses. At 3.8 cm in the soil, the highest maximum temperature recorded was 332°C and the lowest 102°C, with the average temperature of from 110°C to 116°C. Bentley and Fenner (1958) measured maximum temperatures in brush fires resulting in different ash conditions. A maximum temperature of 538°C was measured at the soil surface when white ash was produced, and 177°C when black ash occurred.

Effects of Soil Water on Heating

Soil water is an important consideration during prescribed fire because when the soil and litter are moist, less soil heating occurs. Data collected during the Palomar Fire *(Appendix, table 1)* illustrates the moderating effect of water on soil heating during a fire. Samples of litter and soil contained from 16 to 20 percent water on an oven-dry basis before the fire *(table 1)*. After the fire, much less water was present in the surface ash layer and the 0-1-cm soil layer *(table 1)*.

Table 1—*Water content (by weight) of soil and litter before and aft a prescribed burn of a scrub oak stand near Palomar, Californi*

Depth	Before fire	After fire
	Percent	
$A_{00} + A_0$[1]	16.3	[2]0.8
Cm		
0 to 1	20.1	4.1
1 to 2	16.0	14.2
2 to 3	16.1	19.3
3 to 4	13.9	17.5
4 to 6	15.2	15.4

[1] The A_{00} horizon consists of loose leaves and organic debris largely decomposed; the A_0 horizon consists of organic debris partially decomposed, or matted.

[2] Water content of the surface ash dust layer after the fire.

Some water was apparently translocated downward during the fire because water in the 2- to 3-cm and 3- to 4-cm soil layers increased. The presence of water reduced soil heating significantly at depths of 1 cm or more *(fig. 3)*. Although the surface temperature reached about 538°C, maximum temperature of the 1-cm soil layer was only 82°C. At 3 cm, the temperature increased slightly *(Appendix, table 1, fig. 3)*. This pattern of heating is consistent with results of other studies which have shown that the temperature of a wet soil layer does not increase above the boiling point of water until the water evaporates or is moved into a deeper layer (Aston and Gill 1976, DeBano and others 1976, Scotter 1970). During this vaporization and condensation process, heat, water and organic hydrophobic substances can be transferred simultaneously downward in the soil.

Soil chemical and physical properties undergo less change and any adverse impact of prescribed burning on soil properties is minimized when less soil heating occurs. Soil water can be measured before a burn and, if burning cannot be done over a moist soil, the impact on nutrient loss (e.g., nitrogen) can be weighed against the advantages of burning under less than optimum soil moisture conditions.

Variability of Surface Temperatures

Maximum surface temperatures measured at several locations at a site can vary over short distances *(Ap-*

pendix, table 1). Temperature measurements taken within 90 cm of each other at the Cameron, Palomar, and Paradise Valley prescribed burns provided data on this variation. At Cameron, among the four recorders, maximum temperatures ranged from 632°C to 749°C, with a mean of 682°C, and a standard deviation of 37°C. At Palomar, the maximum temperatures ranged from 416°C to 732°C, with a mean of 567°C, and a standard deviation of 97°C. During the Paradise Valley burn, the average maximum surface temperature on the eight locations monitored was 634°C, with a standard deviation of 68°C, and a range of from 516°C to 782°C.

In addition to the variation in maximum temperatures, large differences in the duration of heating were observed *(fig. 4).* During the Palomar Fire, one site had a heat pulse reaching a maximum of 599°C for a short duration and another nearby site had a maximum temperature of 549°C for a much longer time *(fig. 4).*

Predictions of Heat Effects

Renewed interest in prescribed burning has raised many questions including what soil and litter temperatures can be expected during a typical chaparral fire. Also, temperature data are needed for simulating chaparral fires during laboratory experiments which realistically characterize soil heating during prescribed burns in the field.

Because soil heating varies considerably over short distances *(fig. 4),* we will characterize soil and litter temperatures for only light, moderate, and intense burning. The range of our data *(Appendix, table 1)* represents a gradual transition from very light to extremely intense soil heating, so we selected fires with temperatures representative of different degrees of soil heating that were comparable to previously reported maximum temperatures (Bentley and Fenner 1958, Sampson 1944).

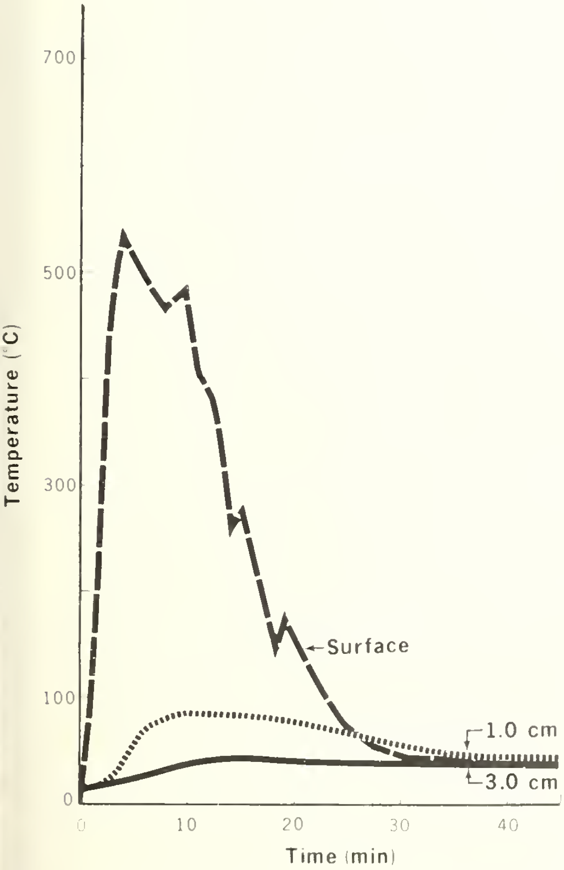


Figure 3—Soil heating at the surface and downward in the soil at Site 1 during a prescribed fire at Mt. Palomar, May, 1973.

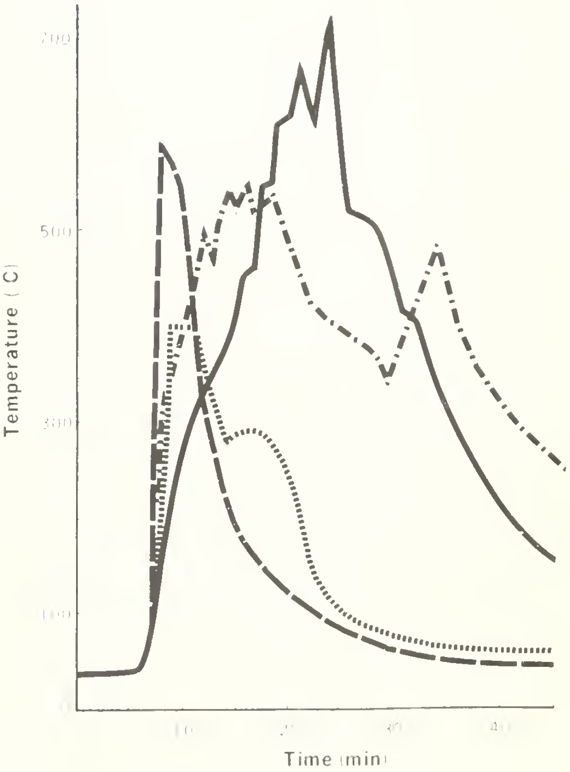


Figure 4—The variation in surface temperatures at four locations within 90 cm of each other at Site 2 during a prescribed burn at Mt. Palomar, May, 1973.

Although light, moderate, and intense burning conditions were not specified by Sampson (1944), or Bentley and Fenner (1958), the maximum temperatures they reported can be related to burning intensity. For example, intense burning appears to correspond well to the "white ash" condition described by Bentley and Fenner (1958). A "white ash" is present after litter and heavy fuels have been completely consumed and a thick ash deposit remains on the soil surface. Although Sampson (1944) did not refer to either an intense burn or a "white ash" condition, he provided data for a fire in a chamise stand with a scattered herb understory where the litter temperature exceeded 649°C. The temperature at 3.8 cm in the soil was 243°C. The soil temperatures present during a moderately intense burn may produce a "bare" condition (Bentley and Fenner 1958) when all litter has been burned and no ash remains. Surface temperatures at 399°C were present when this condition developed (Bentley and Fenner 1958). At the 2.5-cm soil depth, the maximum temperature was 177°C. Sampson (1944) described a fire in wedgeleaf ceanothus with a annual grass understory which corresponded closely t the maximum temperatures reported by Bentley an Fenner for a "bare" condition. Light burning wa characterized by a "black ash" condition where th surface was covered by charred litter fragment (Bentley and Fenner 1958). When the "black ash condition was produced, the maximum litter temperature was 177°C, and the temperature at 2.5 cm wa 71°C. A low intensity fire described by Sampso (1944) in wedgeleaf ceanothus with scattered gras produced a maximum temperature of 149°C in the 1.2 cm of litter, and 93°C at 1.27 cm in the soil.

This published information gave us some guidanc in selecting fire data which represented three burnin intensities. Temperature data from three sites (Site 1 a Paradise Valley, and Sites 5 and 6 at Lone Pine Canyon) were combined to represent the temperature regimes existing in the soil and litter during an intens fire. These data were used to construct a stylized curv describing soil and litter heating during an intense fir

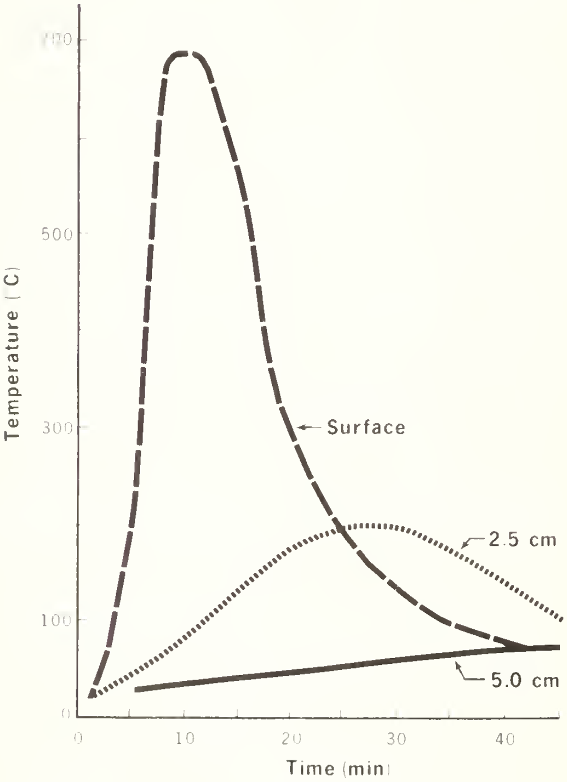


Figure 5—Soil and litter temperatures during an intense chaparral fire.

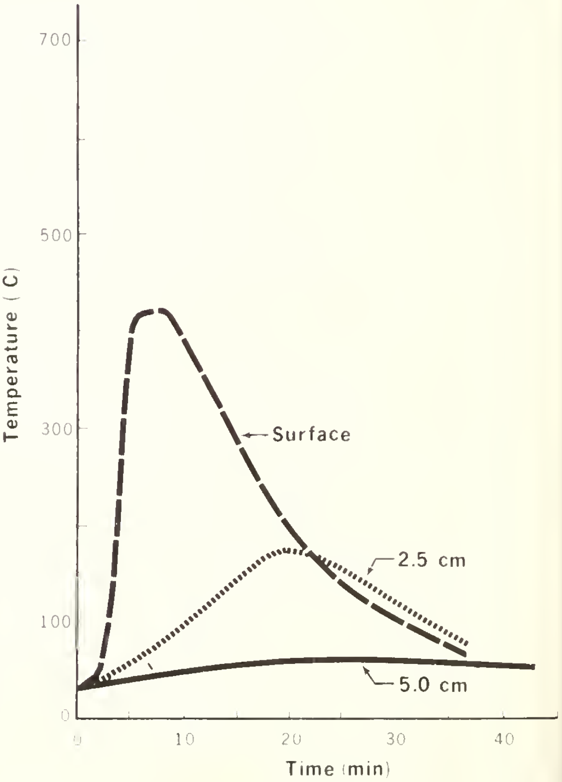


Figure 6—Soil and litter temperatures during a moderately intense chaparral fire.

(fig. 5). The maximum temperature developing at the surface as shown on this curve was slightly higher than that reported by Sampson (1944) and Bentley and Fenner (1958); the maximum temperature at the 2.5-cm depth was 199°C and lower than reported by Sampson (1944) and Bentley and Fenner (1958) *(table 2)*. Data from an additional three fires were used to construct temperature curves representing a moderately intense burn *(fig. 6)*. Data from Sites 1 and 6 at Mission Viejo and Site 4 at North Mountain represent a moderately intense burn. The maximum temperatures of our stylized curve compared very closely with those soil and litter temperatures reported by Sampson (1944) and Bentley and Fenner (1958) *(table 2)*. Only data from Site 8 at Mission Viejo and Site 2 at Lone Pine Canyon were found suitable for developing curves to represent a low intensity burn *(fig. 7)*. The surface temperatures for our stylized curves for the light intensity burn were slightly higher than those reported by Sampson (1944) and Bentley and Fenner (1958), but the soil temperatures were comparable *(table 2)*.

The value of these stylized curves is that the information they provide can be used to predict the degree of soil heating in a given fire situation. Knowing the degree of heating—light, moderate, or intense—and knowing the effects of this degree of heating on soil, plant nutrients, micro-organisms, soil wettability, erosion, and runoff provides the facts necessary to assess correctly the advantages and disadvantages of a burn.

EFFECTS OF FIRE ON CHAPARRAL ECOSYSTEMS

Temperature regimes during light, moderate, and intense soil heating each affect the chaparral ecosystem differently. This section summarizes available information on the effects of fire on chaparral ecosystems. Included is information on soils, plant nutrients, soil wettability, infiltration, runoff, and erosion. When relationships were lacking for chaparral, they were supplemented with appropriate information taken from other vegetation types (e.g., grasslands, forests).

Soils

Information on the physical, chemical, and biological properties of chaparral soils is scant and even less is known about the effects of fire on chaparral soils (DeBano 1974). Most information on soils has been taken incidental to other studies and, although numerous studies have been done on plant succession after chaparral fires, little data has been collected on soil changes. Only a publication by Christensen and Muller (1975) considers detailed changes in soil properties resulting from chaparral fires. This meager "state-of-the-art" on chaparral soils is in sharp contrast to the volumes of published information on the physical, chemical, and biological changes occurring in forest and grassland soils during fire. Many fire-related changes in forest soils are of limited value in chaparral

Table 2—*A comparison of maximum surface, litter, and soil temperatures during intense, moderate, and light burns*

Intensity	Typical maximum temperatures [1]		Data from Sampson (1944)[2]		Data from Bentley and Fenner (1958)	
	Surface	2.5 cm	Litter	Soil	Surface	2.5 cm
	°C					
Intense	691	199	649	243	>538	288
Moderate	427	166	429	202	399	177
Light	249	88	149	93	177	71

[1] Maximum temperatures taken from three stylized curves representing light, moderate, and intense burning conditions.

[2] Temperatures were taken at: 1.3 cm in the litter and 3.8 cm in the soil for the intense burn; 1.3 cm in the litter and 4.5 cm in the soil for the moderate burn; and 1.3 cm in the litter and 1.3 cm in the soil for the light burn. From the author's description, it could not be determined whether the sensor in 1.3 cm of litter was at the soil surface, although the temperatures seemed reasonable for this position.

areas. The sketchy understanding of chaparral soils makes it difficult to apply relationships developed in forest soils to brushland soils, and fire behavior is different in chaparral than in forests.

Although specific information on many heat-induced changes is lacking for chaparral soils, some basic relationships are obvious. First, organic matter in the soil, litter, or standing brush will ignite when heated to 427°C (Gaylor 1974). These temperatures exist at the soil surface during most chaparral fires. Second, when organic matter is destroyed, the physical, chemical, and biological soil properties related to organic matter are also changed. The magnitude of change is directly related to the quantity of organic matter destroyed.

Typically, the soil surface in a chaparral stand is covered with varying amounts of litter, depending upon the species occupying the site and the time since the last fire. The average annual accumulation varies from 1994 to 3942 kg per ha in southern California (Kittredge 1955). Downward in the soil, plant material is in various stages of decomposition and eventually, at some depth, organic matter is no longer discernible as plant material but, instead, imparts only a darkish color to the mineral soil. Although organic matter decreases with depth, substantial amounts can be present in deeper soil layers as plant roots. The root distribution of chaparral brush species may vary from the deep penetrating roots of chamise to the more extensive lateral system under bigberry manzanita where the roots are confined to the upper 0.6 m of soil (Hellmers and others 1955b).

Soil Physical Properties

Soil physical properties change when organic matter is destroyed during burning. Organic matter improves soil aggregation and structure by binding individual soil particles together and creating large pores which allow better water penetration and aeration. When organic matter is destroyed by fire, soil structure also deteriorates. A study by Hosking (1938) showed that humic acids in organic matter can be lost at temperatures below 100°C. About 35 percent of the organic carbon in the soil was contained in the humic acid fraction. At temperatures between 100°C and 200°C, nondestructive distillation of volatile organic substances occurred, while temperatures between 200°C and 300°C removed 85 percent of the organic substances by destructive distillation. At temperatures of 300°C, ignition of carboneous residues commenced, and above 450°C, carboneous residues were completely consumed (Hosking 1938). If we apply these relationships to chaparral soils, we find that an intense burn *(fig. 5)* completely destroys organic matter at the soil surface. Maximum temperatures at the 2.5-cm depth during an intense burn are hot enough to destructively distill a large percent of the organic matter. During moderate burns *(fig. 6)*, surface heating to 432°C is sufficient to destroy most of the litter. A low intensity fire can remove 85 percent of the litter on the soil surface by destructive distillation *(fig. 7)*, but only the humic acids would be altered at 2.5 cm.

Not all studies have shown a deterioration in soil structure by heating. Laboratory experiments using a Hugo and Aiken soil, for example, showed aggregation was increased in the upper 0- to 0.64-cm layer by burning (Scott and Burgy 1956). Temperature of the 0.16- to 0.32-cm layer was over 450°C for more than 30 minutes and should have destroyed the organic matter in this layer. This was confirmed in a separate study where the same investigators found lower bulk densities on burned soils (1.0 gm/cm^3) than on unburned soils (1.4 gm/cm^3) (Burgy and Scott 1953).

Soil Chemical Properties

Fire affects both soil chemical properties and nutrient availability. Soil properties most affected by burning are organic matter, pH, cation exchange capacity, nitrogen, sulfur, divalent cations, and potassium. When organic matter is destroyed by fire, plant nutrients are released and become highly available for plant growth, or loss by erosion.

Cation exchange capacity can be decreased by burning and may remain low for at least 1 year (Christensen and Muller 1975) because exchange sites on organic matter are destroyed. Plant nutrients in the organic matter released by burning are deposited and concentrated on the soil surface. A study on burned and unburned soil under chamise showed the concentrations of acetate-soluble sulfate, potassium, phosphate, total nitrogen, ammonia nitrogen, and nitrate nitrogen were higher in burned soils (Christensen and Muller 1975). Increased solubility of cations after fire is responsible for the commonly observed increase in pH following fire, particularly in the upper soil and ash layers (Christensen and Muller 1975, Sampson 1944, Vogl and Schorr 1972). Usually, however, pH increases only slightly and probably does not significantly affect plant growth (Sampson 1944).

Nitrogen cycling occupies a special role in chaparral ecosystems. It is the nutrient most likely to limit plant growth in chaparral (Hellmers and others 1955a). It is also easily volatilized by heating during a fire. At temperatures above 500°C, 100 percent of the nitrogen in plant and litter material can be lost (White and others 1973). Between 400°C and 500°C, from 75 to 100 percent of the nitrogen is lost; between 300°C and 400°C, from 50 to 75 percent is lost. Between 200°C and 300°C, up to 50 percent of the nitrogen may be lost. Below 200°C, no measurable amounts of nitrogen are lost. These reported losses can be used to estimate nitrogen losses during fires producing different degrees of soil heating. If these nitrogen losses are superimposed over the soil heating graphs used to represent light, moderate,and intense burning *(figs. 5, 6, 7)*, nitrogen losses at the surface and downward in the soil can be estimated. During an intense fire, for example, the surface temperature exceeds 500°C and all the nitrogen in the litter is probably volatilized *(fig. 8)*. At the 2.5-cm depth, temperatures are not high enough to volatilize nitrogen. However, some nitrogen is undoubtedly volatilized in the upper 1.3 to 1.9 cm, and the closer to the surface, the greater the loss. The amount of nitrogen contained in the litter layer varies depending on the quantities of litter present. Measurements taken before a prescribed burn in chaparral near Santa Maria showed that about 150 kg per ha of nitrogen were contained in the litter (DeBano and Conrad 1978). Most of this nitrogen would be volatilized during an intense fire. Nitrogen lost during a fire of moderate intensity is less, although about 75 percent of that in the litter may be lost *(fig. 9)*. In the upper inch of soil only small amounts of nitrogen would be lost. During light intensity fires, less than 50 percent of the nitrogen at the soil surface is lost *(fig. 10)*. Although the soil temperatures in *figs. 7* and *10* were classified as light intensity burns, surface temperatures at some sites never exceeded 149°C *(Appendix, table 1)*. Under these conditions, little or no nitrogen should be lost at this level.

Nitrogen loss not only occurs from the litter and soil during a fire but most of it in the brush plants is also volatilized. The plant canopy probably ignites at about 427°C (Gaylor 1974), and once ignited, the temperature may rise to 1093°C (Green 1970). Temperatures of this magnitude can volatilize large amounts of nitrogen in small live and dead stems. About 134 to 142 kg per ha of nitrogen can be contained in the aboveground biomass of a chaparral stand (DeBano and others 1977, Specht 1969).

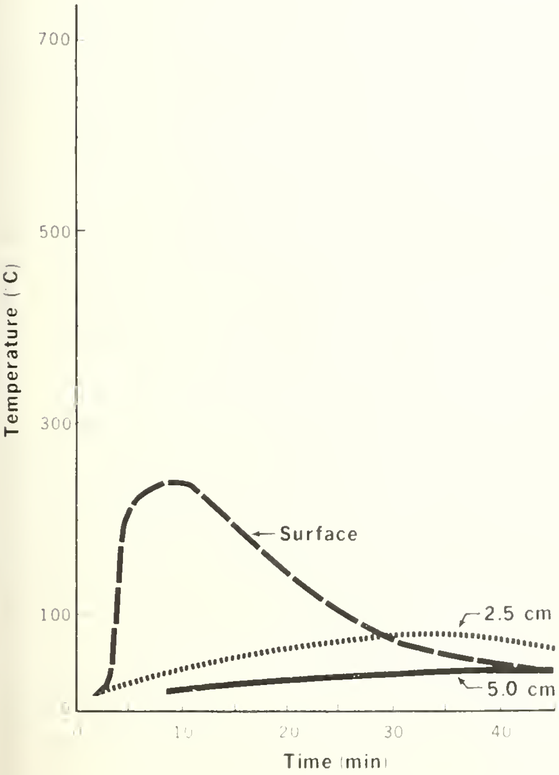


Figure 7—Soil and litter temperatures during a light intensity chaparral fire.

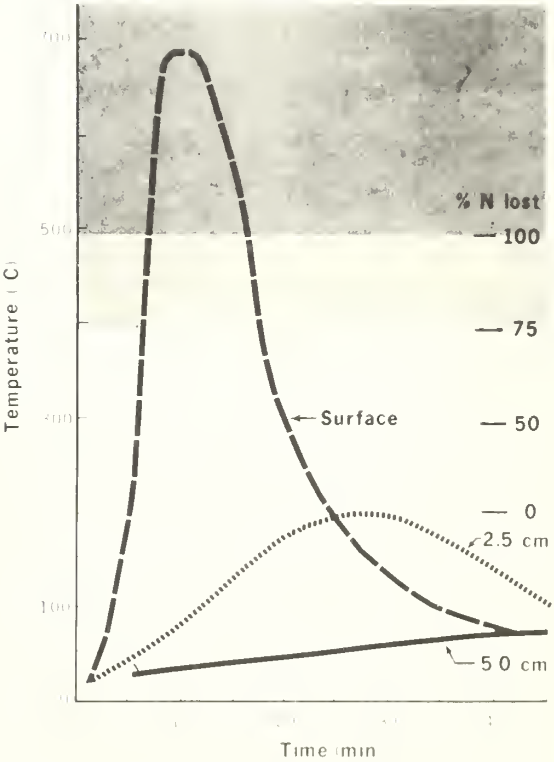


Figure 8—Nitrogen losses during an intense chaparral fire.

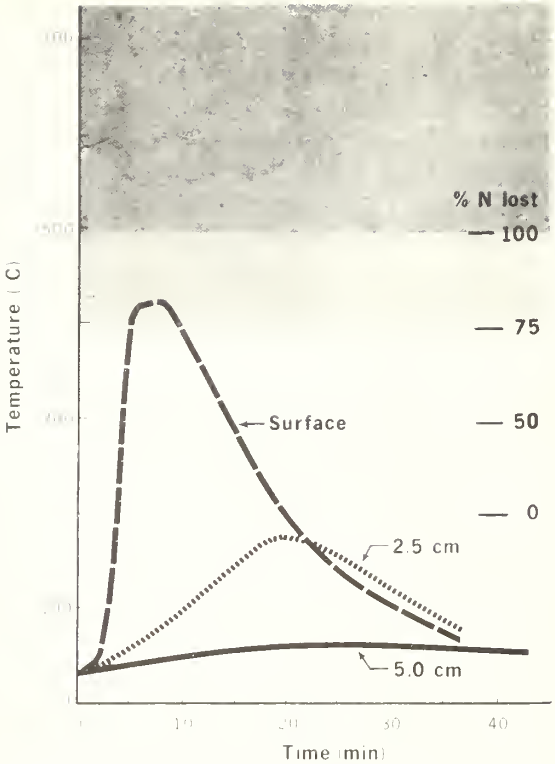


Figure 9—Nitrogen losses during a chaparral fire of moderate intensity.

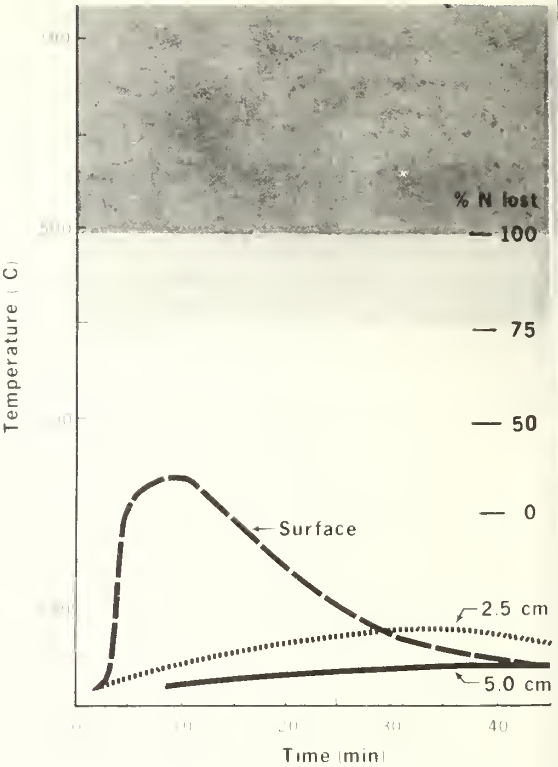


Figure 10—Nitrogen losses during a chaparral fire of low intensity.

Although total nitrogen is lost during a wildfire or prescribed burn, higher concentrations of nitrogen and other plant nutrients have been reported on burned areas than on unburned sites. This contradiction occurs partly because nitrogen is expressed in concentrations rather than in amount per unit area, before and after fire. Knight (1966) illustrated this point well by showing percent nitrogen, in the same experiment, can increase or decrease by merely changing the reference base. If nitrogen is based on ash material remaining after fire, then the concentration will increase; but, if this same amount of nitrogen is based on initial weight of the unburned material, then the percent nitrogen is usually decreased by fire. Another reason nitrogen appears more abundant after fire is because nitrogen availability increases and plant growth is more rapid. Total nitrogen on the site, however, may well have decreased. A way to avoid the pitfall just described, although more time consuming, is to express nutrients in terms of weight per unit area or volume. Recent studies on nutrient cycling have done this.

Soil Micro-organisms

Soil heating directly affects micro-organisms either by killing them or altering their reproductive capability. Indirectly, soil heating alters organic matter, which increases nutrient availability (particularly nitrogen), and stimulates microbial growth rates.

Information is becoming available on the effects of soil heating on micro-organisms in chaparral. One study, which isolated 27 different species of fungi from the soils, concluded that no differences existed between fungal populations on burned and unburned sites (Cooke 1970). Another study (Christensen and Muller 1975) showed substantial differences in fungal and bacterial numbers in wet and dry soil from burned and unburned chaparral areas. Under wet conditions, numbers of bacteria and fungi were higher in the burned chaparral soil than in the unburned. Higher microbial numbers in the burned soil were attributed to an optimum pH and more readily decomposable organic matter.

Results of recent studies in our laboratory show that complex interrelationships exist between soil heating and microbial populations in chaparral soils (Dunn and DeBano 1977). Duration of heating and maximum temperature along with soil water content appear to be the most important factors affecting microbial responses to soil heating. Generally, bacteria are more resistant to heating in both wet and dry soil than are fungi. The lethal temperature for bacteria was found to be 210°C in dry and 110°C in wet soil. Similar lethal temperatures have been reported in forest soils (Ahlgren and Ahlgren 1965) where bacterial numbers were reduced significantly by heating to 200°C for 25 minutes. Fungi in chaparral soils have been found to tolerate temperatures of only 155°C in dry soil and 100°C in wet soil (Dunn and DeBano 1977). In addition to being sensitive to heating, a shift in the species of fungi present occurs as temperature of heating increases. In temperatures up to 120°C in dry and 60°C in wet soil, regular saprophytic fungi prevail; above these temperatures, "heat shock" fungi appear. These "heat shock" fungi persist until they are finally killed at 155°C in dry and 100°C in wet soil.

Nitrifying bacteria appear to be particularly sensitive to soil heating. Experiments in our laboratory have shown *Nitrosomonas* bacteria can be killed in dry soil at temperatures of 140°C and in wet soil at 75°C (Dunn and DeBano 1977). *Nitrobacter* are even more sensitive and are killed at 100°C in dry and 50°C in wet soil. The sensitivity of these nitrifying bacteria to heating has important implications concerning nutrient availability and the nutrition of chaparral plants because nitrogen is frequently a limiting nutrient in chaparral soils (Hellmers and others 1955a). In unburned stands, high levels of the total nitrogen are present as organic nitrogen, and relatively low levels of inorganic mineral nitrogen are present (ammonia and nitrate nitrogen). Christensen (1973) hypothesized that this occurred in unburned stands (a) because heterotrophic micro-organisms responsible for mineralization were inhibited by alleleopathic substances present in chaparral soils, or (b) because the high lignin content of chaparral plant leaves resisted decomposition and subsequent mineralization of nitrogen. After a fire, however, higher concentrations of ammonia and nitrate nitrogen are generally present than are present before burning (Christensen and Muller 1975, Sampson 1944). Recent detailed studies of these inorganic nitrogen compounds before and after burning reveal that ammonia and nitrate nitrogen are formed by different processes in response to a fire. Apparently, large amounts of ammonia nitrogen are produced chemically by soil heating during a fire, and also microbially shortly after burning. Nitrates are not produced directly by heating during a fire, but are formed during subsequent mineralization and nitrification. Postfire nitrification does not appear to be carried out by the classical nitrifying bacteria (*Nitrosomonas* and *Nitrobacter*). These bacteria are extremely sensitive to heating and are absent or at extremely low levels for several months following burning. Results from this study also suggest that nitrification in burned chaparral soils is carried out by fungi.

Any management plan involving winter and summer burning must balance the tradeoffs between soil micro-organisms and nitrogen (Dunn and DeBano 1977). Prescribed burns during the winter over moist soil will be cool and volatilize the least amount of nitrogen from a site. However, micro-organisms are more sensitive to heating in a wet soil than in a dry soil. Results of experiments thus far show that winter burns are cooler and the effect on microbes is about equal to that of most hot, dry summer burns (Dunn and DeBano 1977). It is possible, however, to produce an extremely hot fire over wet soil if a large amount of either crushed or standing dead fuel is burned on dry days during the winter. Under these extreme burning conditions, microbial numbers could be reduced to such low levels that recovery would be hampered. These tradeoffs between micro-organisms and nitrogen must be considered also in terms of both short- and long-term effects on chaparral succession and site productivity.

Plant Nutrients

Nutrient Availability

Both burning and natural biological decomposition release mineral elements from organic matter. Biological decomposition releases most nutrients slowly over time and the nutrients probably are used by plants before they are lost from the site by erosion or seepage. In unburned chaparral, litter decomposition by micro-organisms is slow because it may be inhibited by phytotoxins or a high lignin content (Christensen 1973) and unfavorable decomposition conditions (Olson 1963). Fires burning chaparral brush quickly release nutrients which are highly soluble (Christensen and Muller 1975, Sampson 1944). Although some nitrogen may be volatilized and lost during a fire, the remaining ammonia and nitrate nitrogen are highly available (Christensen 1973, Christensen and Muller 1975, Sampson 1944). The quantity of nutrients available after fire depends on how much organic matter burned. When litter is only partly burned, as during a light intensity burn, most of the unburned plant residue has to undergo further microbial decomposition and mineralization before the nutrients become available for plant growth.

Nutrients are more available after fire, and fertilizing with nitrogen, phosphorus, and sulfur does not produce responses on burned chaparral soils (DeBano and Conrad 1974, Vlamis and Gowans 1961).

Nutrient Loss

Plant nutrients are lost from burned watersheds in runoff water and eroded debris. Unfortunately, most past studies have not measured these amounts.

Some information has been collected recently on nutrient loss after prescribed burning on an area east of Santa Maria in the Los Padres National Forest (DeBano and Conrad 1978). A 42-ha chaparral watershed in this area was burned in August 1973. The soils in the study area were a loamy texture although they contained more clay and silt than soils found further south in the San Gabriel Mountains near Los Angeles. Erosion plots established in the area showed steep-burned plots (50 percent slope) lost larger amounts of plant nutrients during the first rainy season than did plots on gentle slopes (20 percent slope). Most nutrients were lost in the debris with smaller amounts in the runoff water *(table 3)*. The nutrients lost with the debris were probably contained in the organic matter. Organic matter made up 5.6 percent of the debris leaving the steep slopes, and 10.9 percent of the debris leaving the gentle slopes *(table 3)*. There was more organic matter in the debris from the gentle slopes because the runoff water had less transporting ability and carried higher proportions of the less dense organic matter. The erosive power of runoff water from the steep slopes was greater, however, and the debris contained a higher proportion of dense mineral soil. In spite of the difference in organic matter content of the debris, the steep slopes lost about 99 kg per ha more organic matter than did the gentle slopes.

Unusually high amounts of calcium were yielded b the plots probably because the soil and parent rock i the area was calcareous (Bergwall 1973). Analysis c plants, litter, and soil showed high quantities of ca cium. Only small quantities of nutrients were lost fro the unburned control sites *(table 3)*. No erosion oc curred on the unburned plots having gentle slopes, s the only nutrients lost were contained in the runof water.

Nutrient losses reported for the Santa Maria stud may not be useful for predicting losses further south i the San Gabriel Mountains because of different paren material, soils, and climate. The rock material in th Santa Maria area was calcareous sandstones and conglomerates (Bergwall 1973). The San Gabrie Mountains are made up primarily of crystallin metamorphic and granitic rocks (Storey 1948). Thes geologic differences are reflected in the highly calcareous soils at Santa Maria. The 38.1 cm of annua rainfall at the Santa Maria site were also less tha normally occur in chaparral areas of the San Gabriel Mountains. The long term average at the headquarters of the San Dimas Experimental Forest near Los Angeles, California, is about 69 cm annually. Nitrogen, phosphorus, potassium, and sodium losses were probably less at Santa Maria because total erosion is less than would be expected in the San Gabriel Mountains. The amounts of calcium and, perhaps, magnesium lost were probably higher at Santa Maria because the soils are calcareous.

Table 3—*Loss of nutrients by erosion from burned and unburned areas on steep and gentle slopes during the first year after a prescribed burn, southern California, 1973*

Slopes	Total debris	Nutrients in debris						Organic Matter		Total Runoff	Nutrients in runoff water			
		N	P	K	Mg	Ca	Na				K	Mg	Ca	Na
	Kg/ha								*Pct.*	*L/ha x 10⁴*	*Kg/ha*			
							Burned							
Steep	7340	15.08	3.37	19.34	28.02	47.39	2.57	410.4	5.6	78.59	7.67	3.63	20.04	2.00
Gentle	2848	7.50	1.00	7.64	6.15	18.47	0.84	311.5	10.9	58.36	3.26	1.91	9.14	1.29
							Unburned							
Steep	211	0.29	0.08	0.50	0.47	0.52	0.07	7.1	3.4	2.40	0.09	0.07	0.41	0.10
Gentle	0	0	0	0	0	0	0	0	0	0.45	.01	.00	.04	.01

The amounts of plant nutrients lost by erosion depend on several conditions (e.g., total amount of plant nutrients, site, intensity of burn, soil properties . . .). Assuming all other variables equal, however, fire intensity probably affects the amount of plant nutrients lost from a site. Intense fires would be expected to release larger quantities of plant nutrients from the litter and plants than those of low intensity. Loss of organic matter under different fire intensities described earlier may be useful for predicting the amounts of highly soluble nutrients available for erosion after fire.

Soil Wettability

Brush fires can decrease infiltration by producing a water repellent layer. On burned areas, a water repellent layer is frequently found below and parallel to the soil surface (DeBano and others 1967). The soil at or near the surface may be wettable, but a layer of varying thickness below it repels water. The nature of this water repellency can be described by comparing it to the way in which water enters a dry soil. If a water droplet is placed on the surface of wettable soil, it quickly penetrates the dry, wettable soil because there is a strong attraction between the water films and the soil particles. But if a water droplet is placed on the surface of a water repellent soil, it will ''ball-up'' and remain on the soil surface for some time before being absorbed. Although in some cases water repellency is severe enough to completely prohibit water absorption, it usually only impedes absorption for a short time. Severe water repellency in a soil is caused when soil particles are more completely coated with hydrophobic organic substances.

From laboratory and field observations, we have developed a theory of how fire intensifies water repellency *(fig. 11)*. During years between fires, decomposing plant parts containing hydrophobic substances accumulate in the upper part of the soil profile *(fig. 11A)*. This layer corresponds roughly to the A_0 and A_1 soil horizons. The more severe water repellency in this unburned soil probably results when the soil particles are coated with partially decomposed plant parts that are intermixed with mineral soil. Micro-organisms, particularly fungi, also release decomposition products which can induce water repellency in the unburned condition (Bond 1960).

When fire occurs, it consumes the chaparral cover and the underlying litter layer *(fig. 11B)*. An increase in the soil temperature below the soil surface may intensify water repellency in place by coating the soil particles with hydrophobic materials and fixing them in place (Savage 1974). Several investigators have studied the temperatures necessary to intensify or destroy water repellency (Cory and Morris 1969, DeBano and Krammes 1966, Savage 1974, Scholl 1975). These studies indicate both temperature and duration of heating affect the degree of water repellency (that is, intensify or destroy it). When soil containing organic matter is heated for 15 minutes at 204°C to 260°C, water repellency is intensified so water will not penetrate the soil (DeBano and Krammes 1966). If the same soil is heated instead for 15 minutes at 371°C or more, however, the water repellency will be destroyed and the soil will become highly wettable. As the duration of heating is increased, the temperature required to intensify or destroy water repellency is reduced accordingly. Most studies agree that the substances responsible for water repellency are destroyed when heated to over 288°C for short periods. Between 177°C and 204°C, however, water repellency is intensified and can become very severe. During intense burns, therefore, severe water repellency could be produced within 2.5 cm of the soil surface *(fig. 5)*, although the hydrophobic substances would be destroyed at the soil surface. During a moderately intense burn, water repellency would be located closer to the soil surface than for the intense burn, but still could have a thin layer of wettable soil at the surface. During a light intensity burn, it is likely that any water repellency would be found at the soil surface. If the burn is very light, water repellency may be confined to the litter and would not coat the soil particles.

Although the temperature at any particular soil depth during a fire is important for intensifying water repellency in place, vaporization and condensation of organic materials move downward in the soil where they are fixed more tightly by subsequent heating (DeBano 1966, Savage 1974). Large temperature gradients are present during most fires. For example, the temperature dropped 167°C per cm in the upper 2.5-cm layer of soil during an intense burn *(table 2)*. During a moderate burn, the temperature gradient amounts to only 98°C per cm, and during a light burn 49°C per cm. The different temperature gradients would move varying amounts of hydrophobic substances downward during different intensities of burning.

After the fire has swept through an area, the soil has an altered water repellent layer *(fig. 11C)*. As discussed earlier, the thickness and depth of the layer depend on the intensity of the fire and the nature and amount of litter present. If the surface temperatures are not hot during a fire, water repellency might be at or near the soil surface. If the soil were heated to higher temperatures, water repellency could show up in deeper layers, and the surface be wettable.

Soil physical properties and water content also affect the downward movement of hydrophobic substances. Sand and sandy loam soils tend to become more severely water repellent than do finer-textured clay soils (DeBano and others 1970). In coarse-textured soils, organic matter coats the soil particles more completely than it does in finer-textured soils that have a larger amount of particle surface area. In wet soil, hydrophobic substances tend to concentrate in a thin layer near the soil surface; in a dry soil, hydrophobic substances move farther downward in the soil, if temperature gradients allow, causing a thicker water repellent layer (DeBano and others 1976).

Infiltration

The affinity of soils for water can be reduced by coating soil particles with hydrophobic substances (DeBano 1971, 1975). These hydrophobic substances change the apparent liquid-solid contact angle which in turn affects water movement during both evaporation and infiltration (DeBano and others 1967, Letey and others 1962). The resistance to wetting produces anomalies during infiltration. One such anomaly is that water uptake is slower at the beginning of infiltration than after water has been entering the soil for some time (Letey and others 1962). In a normal dry soil that is wettable, the initial infiltration rate is high and decreases exponentially over time until it eventually assumes a constant rate equivalent to the hydraulic conductivity of the soil.

Laboratory studies have shown infiltration rates can be 25 times slower in the water repellent soil than in a similar wettable soil (DeBano 1971). The effect of water repellent soil on infiltration decreases as the soil wets up and, once the water repellent soil has wet up, it transmits water as rapidly as a normal wettable soil—sometimes even faster.

A second peculiarity is that infiltration rates are more rapid in moist soils than in similar air-dry soils (Gilmour 1968). These anomalies probably occur be-

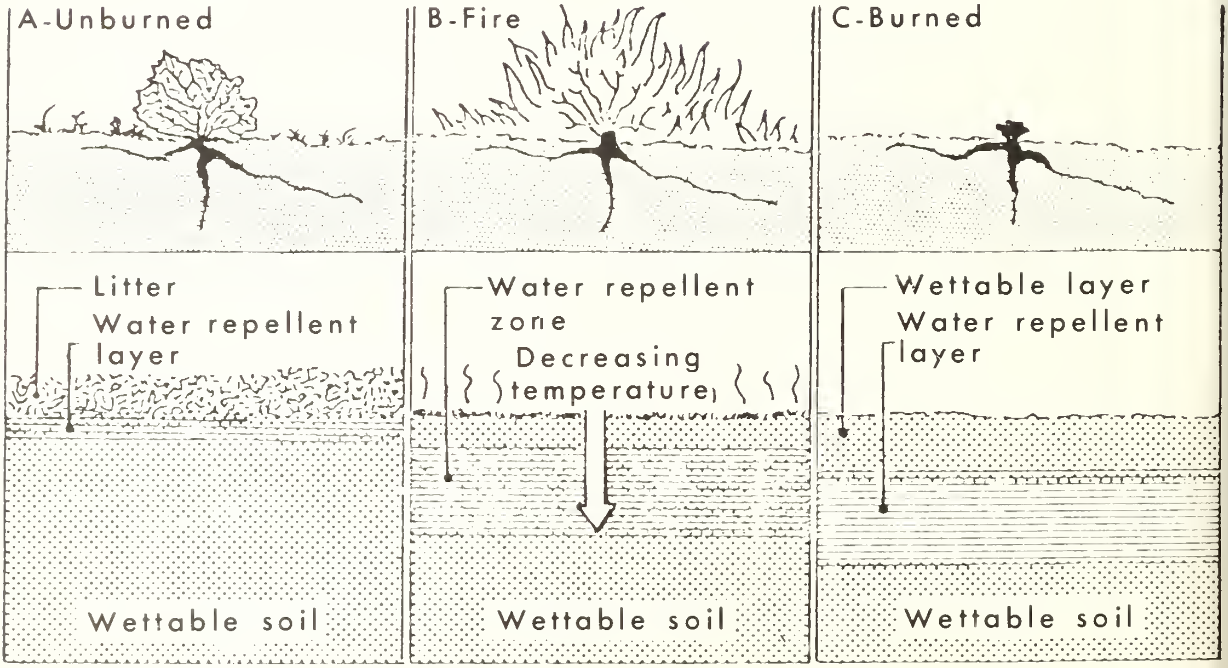


Figure 11—Soil water repellency is altered by fire. *(A)* Before fire, hydrophobic substances accumulate in litter layer and mineral soil immediately beneath it. *(B)* Fire burns vegetation and litter layer, causing hydrophobic substances to move downward along temperature gradients. *(C)* After fire, water repellent layer is present below and parallel to soil surface on burned area.

cause the wettability of the particle surface increases over time when a water repellent soil is placed in contact with water (DeBano 1975).

The high runoff and erosion rates following wildfires in chaparral areas of southern California are thought to be the result of the combined effect of a water repellent soil layer and raindrop splash. On these burned areas, the soil at or near the surface may be wettable, but a layer beneath it repels water. This layered arrangement allows incoming rainfall to infiltrate only a limited depth before the wetting front reaches the water repellent layer *(fig. 12)*. When the thin mantle above the water repellent layer becomes saturated, water flows laterally and runs off. The surface layer is also constantly being churned by incoming raindrops and saturated soil from this upper layer, along with some of the water repellent layer, is easily carried away by surface runoff. Wetting agents used to correct this hard-to-wet condition have reduced runoff 40 percent (Krammes and Osborn 1969). In these studies, runoff from untreated plots ranged from 4.0 to 10.5 cm when the seasonal amounts varied from 20.3 to 94.0 cm.

Runoff and Erosion

Fully vegetated, unburned chaparral watersheds, in common with other forested watersheds, seldom show overland flow. Surface litter promotes infiltration by reducing a raindrop impact and impeding overland flow, thereby providing temporary storage for short periods of high-intensity rainfall. High infiltration rates and the storage capacity of chaparral soil leave little water available for overland flow on the surface. Further, chaparral soils and geologic parent materials are characteristically permeable compared to prevailing rainfall intensities (Krammes 1969). When surface erosion occurs, it is generally restricted to established rills and gullies. As an example of the effect of these characteristics of chaparral watersheds, consider the behavior of research areas on the San Dimas Experimental Forest during a large storm in March 1938. Less than 1 percent of the precipitation was measured as surface runoff on research plots, even though streamflow from various experimental watersheds ranged from 16 to 38 percent of the storm precipitation (Coleman 1953).

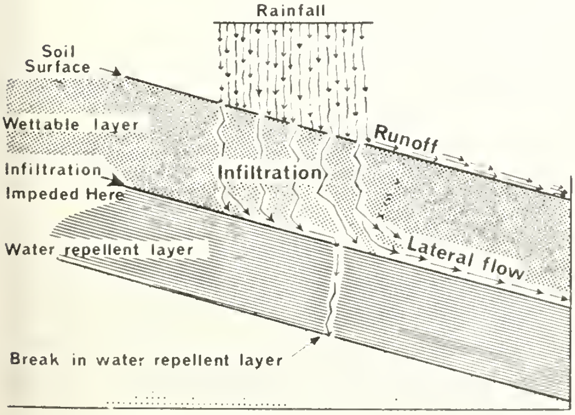


Figure 12—A water repellent layer impedes infiltration and causes surface runoff.

The relative stability of the chaparral watersheds is changed by wildfires and investigators find that high rates of runoff and debris usually follow burning (Krammes 1965, Krammes and Osborn 1969, Rowe 1941, Sinclair 1954). These high runoff rates result partly from a marked intensification of a water repellent layer. This layer greatly decreases infiltration rates and reduces the hydrologically active portion of the watershed surface from a meter or more in thickness to only a few centimeters. This means that relatively small storms and low rainfall intensities can produce substantial amounts of overland flow and result in substantial sheet and rill erosion. DeBano and Conrad (1976) found 34 times more soil and debris moved on a 50 percent slope following a moderately intense prescribed burn than on a similar unburned area. The erosion rate for burned plots was 7340 kg per ha and for unburned plots was 211 kg per ha. It seems reasonable to assume that an increase in overland flow also increases gully erosion. The significance of an increase in overland flow is not that it directly increases erosion; rather, the increased flow provides a transporting mechanism for landslide and dry ravel deposits which have accumulated near the stream channel. On an average, nearly 70 percent of the long term sedimentation movement on chaparral watersheds occurs during the first year after fire (Rice 1974). Most of the increase in sediment does not result from erosion occurring at that time, but results from remobilization of existing deposits.

Debris production from chaparral watersheds seems to be a two-phase process. Although erosion on side slopes is primarily by gravity-activated landslides and dry ravel, some debris is delivered to the channel by overland flow after fires. These processes deliver sediment to gentler slopes (often adjacent to stream channels) where they can no longer operate. From here, flowing water acts as a mechanism for sediment transport. About 25 percent of the chaparral areas are steep enough for gravity-related erosional processes to operate. If erosion were directly related to steepness of slope, this 25 percent of the chaparral would produce about half of the area's sedimentation. Recent data suggest that the proportion of sediment coming from these steep slopes may be much higher. DeBano and Conrad (1976) found that following a prescribed burn, plots on 50 percent slopes yielded about 250 percent more surface erosion than did plots on a 20 percent slope.

Landslides may account for about half the erosion on steep chaparral slopes (Rice 1974). Landslides are relatively infrequent and are dependent upon storms of such a size that they occur only once every 8 years, or less frequently. Consequently, the importance of landslide erosion has been underestimated in the past and few studies have been concerned with measuring it (Rice and Foggin 1971, Rice and others 1969). Data from these studies and the observations of other investigators (Campbell 1975, Scott and Williams 1974), however, tend to support the importance of landslides. Immediately after fire, surface erosion and movement of existing sediment stored in channels dominates the erosion process. Reduced infiltration rates make landslides less likely. Later, landslide erosion on recently burned areas increases because roots of fire-killed vegetation decay. Rice (1974) reported that the volume of landslide erosion on an area which had burned 9 years previously was over 18 times greater than on a chaparral-covered area which had not burned for 50 years. While landslides usually occur during large storms, they often produce debris in excess of the stream's ability to transport it out of the watershed. Such deposits accumulate in a pseudostable condition near stream channels.

Dry ravel produces about one-third of the erosion from steep unburned chaparral watersheds (Rice 1974). Annual rates of dry ravel ranging from 224 to 4300 kg per ha have been measured by Anderson and others (1959). Later, Krammes (1965) found about 45 percent of the surface erosion occurring during the dry season and 55 percent during the wet season. During the wet season, sheet and rill erosion occurred and, in the dry season, dry ravel occurred. A later study (Krammes and Osborn 1969) found that at least one-third, and perhaps as much as three-quarters of the wet season erosion was actually occurring as dry ravel between rainstorms. Taking this into account, we find that from 63 to 86 percent of the surface erosion is dry ravel. Rates of dry ravel erosion are also affected by fire. On an unburned watershed much potentially unstable soil is perched behind stems and litter and prevented from moving downhill by gravity. When the fire destroys these barriers, dry ravel immediately begins. Krammes (1960) measured a nine-fold increase in dry ravel erosion during the first year following fire. In the first 88 days after the fire, 89 percent of this erosion occurred. Since dry ravel occurs when there is little or no streamflow, debris routinely accumulates in deposits at the base of steep slopes. These deposits, together with untransported remnants of landslide debris, act as magazines supplying readily transportable sediments to high stream discharges whenever they occur.

CONCLUSIONS

Soil heating and fire temperatures vary widely between fires and within any particular fire because of differences in fuel loading, weather conditions, and soil water content. Despite these variations, it is possible to use soil temperature data to develop soil heating curves for light, moderate, and intense chaparral fires. The maximum temperatures for these soil heating curves, although stylized, agree well with maximum temperatures reported by other investigators.

The effect of soil heating by these three intensities on many soil physical, chemical, and biological properties is related to the amount of organic matter destroyed. Soil nutrients are either lost by volatilization, or are transformed into highly available ions by burning. Nitrogen, for example, is easily volatilized and lost during burning. The nutrients not volatilized—calcium, magnesium, potassium, sodium, and phosphorus—are released as highly mobile ions which can be metabolized rapidly either by plants or micro-organisms on the sites, or can be lost by erosion and runoff.

Soil heating data during light, moderate, and intense fires can be used to estimate the amounts of nitrogen that can be expected. Up to 100 percent of the nitrogen could be lost from the surface litter layer during an intense chaparral fire.

The effect of soil heating on micro-organisms is less well understood but, undoubtedly, micro-organisms are affected lethally at much lower temperatures than those necessary to change nonliving organic matter.

Erosion rates are high after a fire because ''buffering'' action of vegetation and litter is eliminated, dry ravel and landslides are increased, infiltration is reduced, and peak runoff rates are greatly increased. Peak runoffs carry away substantial amounts of plant nutrients. Light intensity prescribed burns on chaparral areas would be expected to release smaller amounts of plant nutrients and smaller erosional losses of these nutrients would occur.

Differences in erosional rates can result from site differences as well as from variations in soil heating between wildfires and prescribed burns. Steep slopes encourage dry ravel and landslides. Differences in soil and rainfall also affect erosional rates. Despite large site differences, a greater degree of soil heating during a wildfire would be expected to do more damage to the site than would a cooler, prescribed burn.

LITERATURE CITED

Ahlgren, Isabel F., and Clifford E. Ahlgren.
1965. **Effects of prescribed burning on soil microorganisms in a Minnesota jack pine forest.** Ecology 46(3):304-310.

Anderson, H.W., G.B. Coleman, and P.J. Zinke.
1959. **Summer slides and winter scour . . . dry-wet erosion in southern California mountains.** USDA Forest Serv. Tech. Paper 36, 12 p., illus. Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif.

Aston, A.R., and A.M. Gill.
1976. **Coupled soil moisture, heat and water vapour transfers under simulated fire conditions.** Aust. J. Soil Res. 14:55-66.

Bentley, J.R., and R.L. Fenner.
1958. **Soil temperatures during burning related to postfire seedbeds on woodland range.** J. For. 56:737-740.

Bergwall, Frank.
1973. **Geology and soils report. Paradise burn, Stanley-Logan-Wilcox fuelbreak, Santa Lucia Ranger District, Santa Maria, Calif.** 26 p.

Biswell, Harold H.
1975. **Effects of fire on chaparral.** *In* Fire and ecosystems. T.T. Kozlowski and C.E. Ahlgren, eds. p. 321-364. Academic Press, New York.

Bond, R.D.
1960. **The occurrence of microbial filaments in soils and their effect on some soil properties.** C.S.I.R.O., Div. of Soils, Div. Rep. 10/60, 9 p.

Burgy, R.H., and V.H. Scott.
1953. **Discussion of "some effects of fire and ash on the infiltration capacity of soils."** Trans. Amer. Geophys. Union 34(2):293-295.

Campbell, Russell H.
1975. **Soil slips, debris flows, and rainstorms in the Santa Monica Mountains and vicinity, southern California.** U.S. Geol. Surv. Prof. Paper 851, 51 p.

Christensen, Norman L.
1973. **Fire and the nitrogen cycle in California chaparral.** Science 181(4094):66-68.

Christensen, Norman L., and Cornelius H. Muller.
1975. **Effects of fire on factors controlling plant growth in *Adenostoma* chaparral.** Ecol. Monogr. 45(1):29-55.

Colman, E.A.
1953. **Fire and water in southern California's mountains.** Calif. Forest and Range Exp. Stn., Misc. Paper 3, USDA Forest Serv., Berkeley, Calif. 8 p.

Cooke, Wm. Bridge.
1970. **Fungi in burned and unburned chaparral soils.** Sydowia, Ann. Mycol., Ser. 2, 24:164-168.

Cory, John T., and Robert J. Morris.
1969 **Factors restricting infiltration rates on decomposed granitic soils.** *In* Symposium Water Repellent Soils Proceedings [Riverside, Calif., May 6-10, 1968], L.F. DeBano and J. Letey (eds.). p. 149-161. Univ. Calif., Riverside.

Countryman, Clive M.
1964. **Mass fires and fire behavior.** USDA Forest Serv. Res. Paper PSW-19, 53 p., illus. Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif.

DeBano, Leonard F.
1966. **Formation of non-wettable soils . . . involves heat transfer mechanism.** USDA Forest Serv. Res. Note PSW-132, 8 p., illus. Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif.

DeBano, Leonard F.
1971. **The effect of hydrophobic substances on water movement during infiltration.** Soil Sci. Soc. Amer. Proc. 35:340-343.

DeBano, L.F.
1974. **Chaparral soils.** *In* Symposium on Living with the Chaparral Proceedings [Riverside, Calif., March 30-31, 1973], p. 19-26, Sierra Club.

DeBano, L.F.
1975. **Infiltration, evaporation, and water movement as related to water repellency.** *In* "Soil Conditioners," Soil Sci. Soc. Amer. Proceedings Spec. Publ. 7:155-163.

DeBano, Leonard F., and C. Eugene Conrad.
1974. **Effect of a wetting agent and nitrogen fertilizer on establishment of ryegrass and mustard on a burned watershed.** J. Range Manage. 27(1):57-60.

DeBano, L.F., and C.E. Conrad.
1976. **Nutrients lost in debris and runoff water from a burned chaparral watershed.** Third Inter-Agency Sedimentation Conference [Denver, Colo., March 1976] Proceedings, p. 3-13 to 3-27.

DeBano, L.F., and C.E. Conrad.
1978. **The effect of fire on nutrients in a chaparral ecosystem.** Ecology 59(3):489-497.

DeBano, L.F., and J.S. Krammes.
1966. **Water repellent soils and their relation to wildfire temperatures.** Bull. I.A.S.H., XI Année No. 2, p. 14-19, illus.

DeBano, L.F., and Raymond M. Rice.
1971. **Fire in vegetation management: its effects on soil. Symposium on Interdisciplinary Aspects of Watershed Management Proceedings** [Bozeman, Mont., August 1970], illus., p. 327-346.

DeBano, L.F., P.H. Dunn, and C.E. Conrad.
1977. **Fire's effect on physical and chemical properties of chaparral soils.** *In* International Symposium on the Environmental Consequences of Fire and Fuel Management in Mediterranean Climate Ecosystems [Palo Alto, Calif., August

1-5, 1977], p. 65-74. USDA Forest Serv. Gen. Tech. Rep. WO-3, 498 p.

DeBano, L.F., L.D. Mann, and D.A. Hamilton.
1970. **Translocation of hydrophobic substances into soil by burning organic litter.** Soil Sci. Soc. Amer. Proceedings 34(1):130-133.

DeBano, L.F., S.M. Savage, and D.A. Hamilton.
1976. **The transfer of heat and hydrophobic substances during burning.** Soil Sci. Soc. Amer. Proceedings 40:779-782.

DeBano, Leonard F., Joseph F. Osborn, Jay S. Krammes, and John Letey, Jr.
1967. **Soil wettability and wetting agents . . . our current knowledge of the problem.** USDA Forest Serv. Res. Paper PSW-43, 13 p., illus. Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif.

Dunn, P.H., L.F. DeBano, and G.E. Eberlein.
1979. **Effects of burning on chaparral soils. II. Soil microbes and nitrogen mineralization.** Soil Sci. Soc. Amer. J. 43:509-514.

Dunn, Paul H., and Leonard F. DeBano.
1977. **Fire's effect on the biological and chemical properties of chaparral soils.** *In* International Symposium on the Environmental Consequences of Fire and Fuel Management in Mediterranean Climate Ecosystems [Palo Alto, Calif., August 1-5, 1977], p. 75-84. USDA Forest Serv. Gen. Tech Rep. WO-3, 498 p.

Gaylor, Harry P.
1974. **Wildfires—prevention and control.** 319 p. Prentice-Hall Co., Bowie, Maryland.

Gilmour, D.A.
1968. **Water repellence of soils related to surface dryness.** Aust. For. 32:143-148.

Green, Lisle R.
1970. **An experimental prescribed burn to reduce fuel hazard in chaparral.** USDA Forest Serv. Res. Note PSW-216, 6 p. Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif.

Hellmers, Henry, James F. Bonner, and John M. Kelleher.
1955a. **Soil fertility: a watershed management prohlem in the San Gabriel Mountains of southern California.** Soil Sci. 80(3):189-197.

Hellmers, H., J.S. Horton, G. Juhren, and J. O'Keefe.
1955b. **Root systems of some chaparral plants in southern California.** Ecology 36(4):667-678.

Hosking, J.S.
1938. **The ignition at low temperatures of the organic matter in soils.** J. Agric. Sci. 38(3):393-400.

Kittredge, Joseph.
1955. **Litter and forest floor of the chaparral in parts of the San Dimas Experimental Forest, California.** Hilgardia 23(13):563-596.

Knight, H.
1966. **Loss of nitrogen from the forest floor by burning.** For. Chron. 42(2):149-152.

Krammes, Jay S.
1960. **Erosion from mountain side slopes following fire in southern California.** USDA Forest Serv. Res. Note PSW-171, 8 p. Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif.

Krammes, Jay S.
1965. **Seasonal debris movement from steep mountainside slopes in southern California.** Federal Interagency Sedimentation Conference [Oxford, Miss., January 28-February 1, 1963]. Proceedings, U.S. Dep. Agric. Misc. Publ. 970, p. 85-88.

Krammes, J.S., and J. Osborn.
1969. **Water-repellent soils and wetting agents as factors influencing erosion.** *In* Symposium Water Repellent Soils Proceedings [Riverside, Calif., May 6-10, 1968], L.F. DeBano and J. Letey (eds.). p. 177-187. Univ. Calif., Riverside.

Krammes, Jay Samuel.
1969. **Hydrologic significance of the granitic parent materia of the San Gabriel Mountains, California.** Ph.D. dissertation, Oregon State Univ., Corvallis, June 1969.

Lawrence, George E.
1966. **Ecology of vertebrate animals in relation to chaparral fire in the Sierra Nevada foothills.** Ecology 47(2):278-291.

Letey, J., J. Osborn, and R.E. Pelishek.
1962. **The influence of the water-solid contact angle on water movement in soil.** Bull. Int. Assoc. Sci. Hydrol. 3:75-81, illus.

Muller, Cornelius H., Ronald B. Hanawalt, and James K. McPherson.
1968. **Allelopathic control of herb growth in the fire cycle of California chaparral.** Bull. Torrey Bot. Club 95(3):225-231.

Olson, Jerry S.
1963. **Energy storage and the balance of producers and decomposers in ecological systems.** Ecology 44(2):322-331.

Rice, Raymond M.
1974. **The hydrology of chaparral soils.** *In* Symposium On Living with the Chaparral Proceedings [Riverside, Calif., March 30-31, 1973], p. 27-34. Sierra Club.

Rice, R.M., and G.T. Foggin III.
1971. **Effect of high intensity storms on soil slippage on mountainous watersheds in southern California.** Water Resour. Res. 7(6):1485-1496.

Rice, R.M., E.S. Corbett, and R.G. Bailey.
1969. **Soil slips related to vegetation, topography, and soil in southern California.** Water Resour. Res. 5(3):647-659.

Rowe, P.B.
1941. **Some factors of the hydrology of the Sierra Nevada foothills.** Natl. Res. Counc., Amer. Geophys. Union Trans. 1941. p. 90-101.

Sampson, Arthur W.
1944. **Plant succession on hurned chaparral lands in northern California.** Univ. Calif., Coll. Agric., Agric. Exp. Stn. Bull. 685. 144 p.

Savage, S.M.
1974. **Mechanism of fire-induced water repellency in soil.** Soil Sci. Soc. Amer. Proc. 38(4):652-657.

Scholl, David G.
1975. **Soil wettability and fire in Arizona chaparral.** Soil Sci. Soc. Amer. Proc. 39:356-361.

Scott, Keven M., and Rhea P. Williams.
1974. **Erosion and sediment yields in mountain watersheds of the Transverse Ranges, Ventura and Los Angeles Counties, California—analysis of rates and processes.** U.S. Geol. Surv., Water Resour. Investigation 47-73, 66 p.

Scott, V.H., and R.H. Burgy.
1956. **Effects of heat and brush burning on the physical properties of certain upland soils that influence infiltration.** Soil Sci. 82: 63-70.

Scotter, D.R.
1970. **Soil temperatures under grass fires.** Aust. J. Soil Res. 8:273-279.

Sinclair, J.D.
1954. **Erosion in the San Gabriel Mountains of California.** Trans. Amer. Geophys. Union 35(2):264-268.

Specht, R.L.
1969. **A comparison of the sclerophyllous vegetation charac-**

teristic of Mediterranean type climates in France, California, and Southern Australia: II. Dry matter, energy, and nutrient accumulation. Aust. J. Bot. 17:293-308.

Storey, H.C.
1948. **Geology of the San Gabriel Mountains, California, and its relation to water distribution.** Calif. Nat. Resour., Div. For. p. 1-19.

U.S. Department of Agriculture, Forest Service.
1977. **Evaluation of fire management activities on the National Forests.** Policy Anal. Staff Rep., Forest Serv., U.S. Dep. Agric., November 1977.

Vlamis, J., and K.D. Gowans.
1961. **Availability of nitrogen, phosphorus, and sulfur after brush burning.** J. Range Manage. 14(1):38-40.

Vogl, Richard J., and Paul K. Schorr.
1972. **Fire and manzanita chaparral in the San Jacinto Mountains, California.** Ecology 53(6):1179-1188.

White, E.M., W.W. Thompson, and F.R. Gartner.
1973. **Heat effects on nutrient release from soils under ponderosa pine.** J. Range Manage. 26(1):22-24.

APPENDIX

Table 1—*Maximum surface and soil temperatures measured at different burn sites (1968-75)*

Burn	Type of burn	Vegetation	Soil moisture	Date and time	Site	Location of measurement	Maximum temperature (°C)[1]
Mission Viejo	Prescribed burn for range improvement	Dense chamise and *Salvia*	Dry	9/4/68	1	Surface	382
				1230		2.5 cm	66
						5.0 cm	49
		Dense scrub oak	Dry	9/4/68	2	Surface	282
				1600		2.5 cm	66
						5.0 cm	49
		Grassy canyon bottom dense tree canopy	Dry	9/4/68	3	Surface	516
				1500		2.5 cm	57
						5.0 cm	57
						10.0 cm	38
		Dense oak with grass understory	Dry	9/5/68	6	Surface	432
				1130		2.5 cm	166
						5.0 cm	29
		Scrub oak	Dry	9/5/68	7	Surface	216
				1400		2.5 cm	74
						5.0 cm	54
		Scrub oak	Dry	9/5/68	8	Surface	116
				1415		2.5 cm	57
						5.0 cm	35
Lone Pine Canyon	Wildfire	Chamise	Dry	9/8/68	1	Surface	641
				1630		2.5 cm	82
						5.0 cm	43
						10.0 cm	27
		Chamise	Dry	9/8/68	2	Surface	299
				1910		2.5 cm	91
						5.0 cm	43
		Chamise	Dry	9/8/68	3	Surface	166
				1905		2.5 cm	49
						5.0 cm	32
Lone Pine Canyon	Wildfire	Mixed chaparral *Ceanothus*, chamise (light to moderate density)	Dry	9/9/68	4	Surface	716
				1330		2.5 cm	91
						5.0 cm	43
		Mixed chaparral *Ceanothus*, chamise	Dry	9/9/68	5	Surface	616
				1330		2.5 cm	174
						5.0 cm	66
		Dense stand mixed chaparral	Dry	9/9/68	6	Surface	716
				1730		2.5 cm	124
						5.0 cm	54
North Mountain	Experimental burn (Green 1970)	Mixed chaparral	Dry	6/26/69	1	Surface	569
				1430		Surface	607
						1 cm	222
						2 cm	219
						3 cm	167

Table 1—*Maximum surface and soil temperatures measured at different burn sites (1968-75)* (continued)

Burn	Type of burn	Vegetation	Soil moisture	Date and time	Site	Location of measurement	Maximum temperature (°C)[1]
		Mixed chaparral	Dry	6/26/69 1430	4	Surface	382
						2.5 cm	132
						5.0 cm	49
						10.0 cm	24
North Mountain	Experimental burn	Mixed chaparral chamise, manzanita	8 pct.	4/24/70 1330	1	Surface	516
			10 pct.			1 cm	516
			15 pct.			2 cm	277
			15 pct.			4 cm	82
		Mixed chaparral chamise, manzanita heavy concentration of fuel	(same as site 1)		2	Surface	843
						1 cm	499
						2 cm	410
						4 cm	204
Cameron (San Diego County)	Prescribed burn, fuel modification	Scrub oak		6/28/72 1030	1	Surface	[2]427
						1 cm	177
			5 pct.			2 cm	66
						4 cm	46
Cameron (San Diego County)	Prescribed burn, fuel modification	Scrub oak	5 pct.	6/28/72	2	Surface	649
						Surface	716
						Surface	632
						Surface	749
Palomar (San Diego County)	Prescribed burn, fuel modification	Scrub oak, manzanita	[3]16 pct.	5/8/73 1300	1	Surface	538
						1 cm	82
						3 cm	43
					2	Surface	732
						Surface	599
						Surface	416
						Surface	549
Paradise Valley (east of Santa Maria)	Test plots burned before prescribed fire	*Ceanothus*, crushed chamise	Dry	9/7/73 1130	1	Surface	649
						Surface	516
						Surface	549
						Surface	599
			Dry	9/7/73 1130	3	Surface	782
						Surface	649
						Surface	716
						Surface	616
Pine Canyon	Prescribed burn for experimental study	Chamise with small amounts of *Salvia* and manzanita	10 pct.	2/28/73	1	Surface	600
			9 pct.			1 cm	250
			9 pct.			3 cm	60
			11 pct.		2	Surface	650
			12 pct.			1 cm	370
			11 pct.			3 cm	85
			7 pct.		3	Surface	320
			8 pct.			1 cm	160
			12 pct.			3 cm	60

[1] Taken from continuous temperature measurements. Does not include data obtained from tempils.

[2] Exceeded limits of recorder chart (5 minutes >427°C).

[3] Soil water contents before burning. See *table 3* for change in water content during fire.

The Forest Service of the U.S. Department of Agriculture

. . . Conducts forest and range research at more than 75 locations from Puerto Rico to Alaska and Hawaii.

. . . Participates with all State forestry agencies in cooperative programs to protect and improve the Nation's 395 million acres of State, local, and private forest lands.

. . . Manages and protects the 187-million-acre National Forest System for sustained yield of its many products and services.

The Pacific Southwest Forest and Range Experiment Station

represents the research branch of the Forest Service in California and Hawaii.

DeBano, Leonard F., Raymond M. Rice, and C. Eugene Conrad.
1979. **Soil heating in chaparral fires: effects on soil properties, plant nutrients, erosion, and runoff.** Res. Paper PSW-145, 21 p., illus. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

This state-of-the-art report summarizes what is known about the effects of heat on soil during chaparral fires. It reviews the literature on the effects of such fires on soil properties, availability and loss of plant nutrients, soil wettability, erosion, and surface runoff. And it reports new data collected during recent prescribed burns and a wildfire in southern California. From the data, stylized curves that characterize soil heating during light, moderate, and intense chaparral fires were developed. The information is useful in estimating the effects of fire on soils in chaparral ecosystems.

Retrieval Terms: chaparral; brush fires; soil heating; heat effects.

DeBano, Leonard F., Raymond M. Rice, and C. Eugene Conrad.
1979. **Soil heating in chaparral fires: effects on soil properties, plant nutrients, erosion, and runoff.** Res. Paper PSW-145, 21 p., illus. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

This state-of-the-art report summarizes what is known about the effects of heat on soil during chaparral fires. It reviews the literature on the effects of such fires on soil properties, availability and loss of plant nutrients, soil wettability, erosion, and surface runoff. And it reports new data collected during recent prescribed burns and a wildfire in southern California. From the data, stylized curves that characterize soil heating during light, moderate, and intense chaparral fires were developed. The information is useful in estimating the effects of fire on soils in chaparral ecosystems.

Retrieval Terms: chaparral; brush fires; soil heating; heat effects.

DeBano, Leonard F., Raymond M. Rice, and C. Eugene Conrad.
1979. **Soil heating in chaparral fires: effects on soil properties, plant nutrients, erosion, and runoff.** Res. Paper PSW-145, 21 p., illus. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

This state-of-the-art report summarizes what is known about the effects of heat on soil during chaparral fires. It reviews the literature on the effects of such fires on soil properties, availabilty and loss of plant nutrients, soil wettability, erosion, and surface runoff. And it reports new data collected during recent prescribed burns and a wildfire in southern California. From the data, stylized curves that characterize soil heating during light, moderate, and intense chaparral fires were developed. The information is useful in estimating the effects of fire on soils in chaparral ecosystems.

Retrieval Terms: chaparral; brush fires; soil heating; heat effects.

DeBano, Leonard F., Raymond M. Rice, and C. Eugene Conrad.
1979. **Soil heating in chaparral fires: effects on soil properties, plant nutrients, erosion, and runoff.** Res. Paper PSW-145, 21 p., illus. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

This state-of-the-art report summarizes what is known about the effects of heat on soil during chaparral fires. It reviews the literature on the effects of such fires on soil properties, availabilty and loss of plant nutrients, soil wettability, erosion, and surface runoff. And it reports new data collected during recent prescribed burns and a wildfire in southern California. From the data, stylized curves that characterize soil heating during light, moderate, and intense chaparral fires were developed. The information is useful in estimating the effects of fire on soils in chaparral ecosystems.

Retrieval Terms: chaparral; brush fires; soil heating; heat effects.

PACIFIC SOUTHWEST
Forest and Range
Experiment Station

T SERVICE
ARTMENT OF AGRICULTURE

CLEMSON UNIVERSITY LIBRARY
MAR 31 1980
SCI., TECH. & AGR. DIV.

A Watershed's Response to Logging and Roads:

South Fork of Caspar Creek, California, 1967-1976

Raymond M. Rice

Forest B. Tilley

Patricia A. Datzman

RESEARCH PAPER PSW-14

The Authors

RAYMOND M. RICE is principal hydrologist in charge of the Station's research on management of forests on unstable lands, with headquarters in Arcata, California. He joined the Station staff in 1956. He earned a B.S. degree (1951) in forestry from University of Montana, M.S. degree (1961) in forestry from University of California, Berkeley, and Ph.D. degree in watershed management from Colorado State University. **FOREST B. TILLEY**, manager of Jackson State Forest, California Department of Forestry, has a B.S. degree in forestry (1965) from Humboldt State College. **PATRICIA A. DATZMAN**, hydrologist, Bakersfield District, Bureau of Land Management, U.S. Department of Interior, Bakersfield, California, received a B.S. degree (1974) in natural resources and a M.S. degree (1978) in watershed management from Humboldt State University. At the time of the study reported in this paper, she was assigned to National Forests in northern California.

Watershed's Response to Logging and Roads:

South Fork of Caspar Creek, California, 1967-1976

Raymond M. Rice Forest B. Tilley Patricia A. Datzman

CONTENTS

Introduction 1

Caspar Creek Watershed 1

Methods 2

  Streamflow 2

  Suspended Sediment 2

  Debris Basin Accumulation 3

  Calibration Equations 3

Results 5

  Road Construction 5

  Logging 5

Interpretations 7

  Mechanisms 7

  Soil Loss 9

  Water Quality 10

  Comparison to Other Logging 10

Conclusions 12

Literature Cited 12

Pacific Southwest Forest and Range Experiment Station
P.O. Box 245
Berkeley, California 94701

August 1979

IN BRIEF . . .

Rice, Raymond M., Forest B. Tilley, and Patricia A. Datzman.
1979. **A watershed's response to logging and roads: South Fork of Caspar Creek, California, 1967-1976.** Res. Paper PSW-146, 12 p., illus. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.
Retrieval Terms: road construction; logging roads; logging effects; erosion; sedimentation; sediment load; Caspar Creek, California

A long-term study of the effects of logging and roadbuilding on streamflow and sedimentation is underway at Caspar Creek, near Fort Bragg, California. Two experimental watersheds are being studied: North Fork and South Fork of the Creek. The study is a joint effort by the Pacific Southwest Forest and Range Experiment Station and the California Department of Forestry. Results of the first 14 years of the study are reported here.

The forest in the South Fork, the logged watershed, was about 85 years old in 1962, when the study was begun. It consisted mainly of redwood, Douglas-fir, Grand fir, and hemlock. In summer 1967, 4.2 miles (6.8 km) of logging roads were built. The effects of that activity were measured for 4 years and then, during 1971-73, about 65 percent of the stand volume was removed. On-site erosion, annual suspended sediment loads, and debris basin accumulations were estimated in order to evaluate the effects of road construction and the timber harvest.

Erosion associated with logging was measured on seven plots totaling 94 acres (38 ha). They were distributed throughout the watershed so as to be representative of site variability and the three seasons of cutting. Suspended sediment load was estimated each year by multiplying the volume of flow in each of 19 discharge classes by the mean suspended sediment concentration in each class and summing. Annual debris basin accumulations were estimated by comparing annual surveys of the basins. Two regression equations were computed in order to predict the effects of roadbuilding and logging. They estimated the suspended sediment load or debris basin accumulation in the South Fork based on streamflow and suspended sediment load or debris basin accumulation in the North Fork.

During logging, an additional 0.7 mile (1.1 km) of spur road was constructed. Of the total 4.9 miles (7.9 km) of roads, 2.4 miles (3.9 km) of the main haul road, and 1.3 miles (2.1 km) of spur roads were within 200 feet (61 m) of the stream. During the 4 years of measurement before logging began, we estimated that 1304 cu yd/sq mi (385 m^3/km^2) excess sedimentation occurred, or about 80 percent above the amount that would be predicted for the South Fork in an undisturbed condition.

The South Fork watershed produced a total of 4787 cu yd/sq mi (1413 m^3/km^2) excess sediment during the 5 years after logging was started. This sediment represents nearly a threefold increase over that which would have been expected had the watershed remained undisturbed. Analysis of the sediment/stream power relationship of Caspar Creek strongly suggests that the reason for the increase in sedimentation is that logging and roadbuilding had made additional sediment available for transport. In the undisturbed condition, the

Caspar Creek watersheds showed relatively modest increases in sediment load as stream power increased. After disturbance, the South Fork showed substantial increases in sediment transport as stream power increased. The undisturbed regime was highly dependent on supply; the disturbed regime became more dependent on stream power.

The erosion and sedimentation data collected as part of this study were used to estimate the long-term impacts of repeating such disturbances at 50-year intervals. If the estimated erosion rate reflected losses of soil from the site, the soil would be completely eroded in about 7900 years. If, on the other hand, excess sedimentation rates were a better measure of soil loss, exhaustion would occur in about 34,000 years. Either of these estimates is so far beyond current planning horizons that they have little relevance to current management until they are more accurately estimated.

Activities in the South Fork of Caspar Creek may have resulted in turbidities in excess of those permitted by local water quality regulations. Turbidity was not measured as part of this study but because of the nature of the suspended sediment load of Caspar Creek, turbidity increases would probably parallel closely the observed suspended sediment increases. If that is true, then the average turbidity of the South Fork exceeded background by more than 20 percent (the limit set by regulation) in 8 of the 9 years after road construction was started.

Data recorded at weirs in the Caspar Creek drainage in northern California will show effects of logging and roadbuilding on streamflow and water quality.

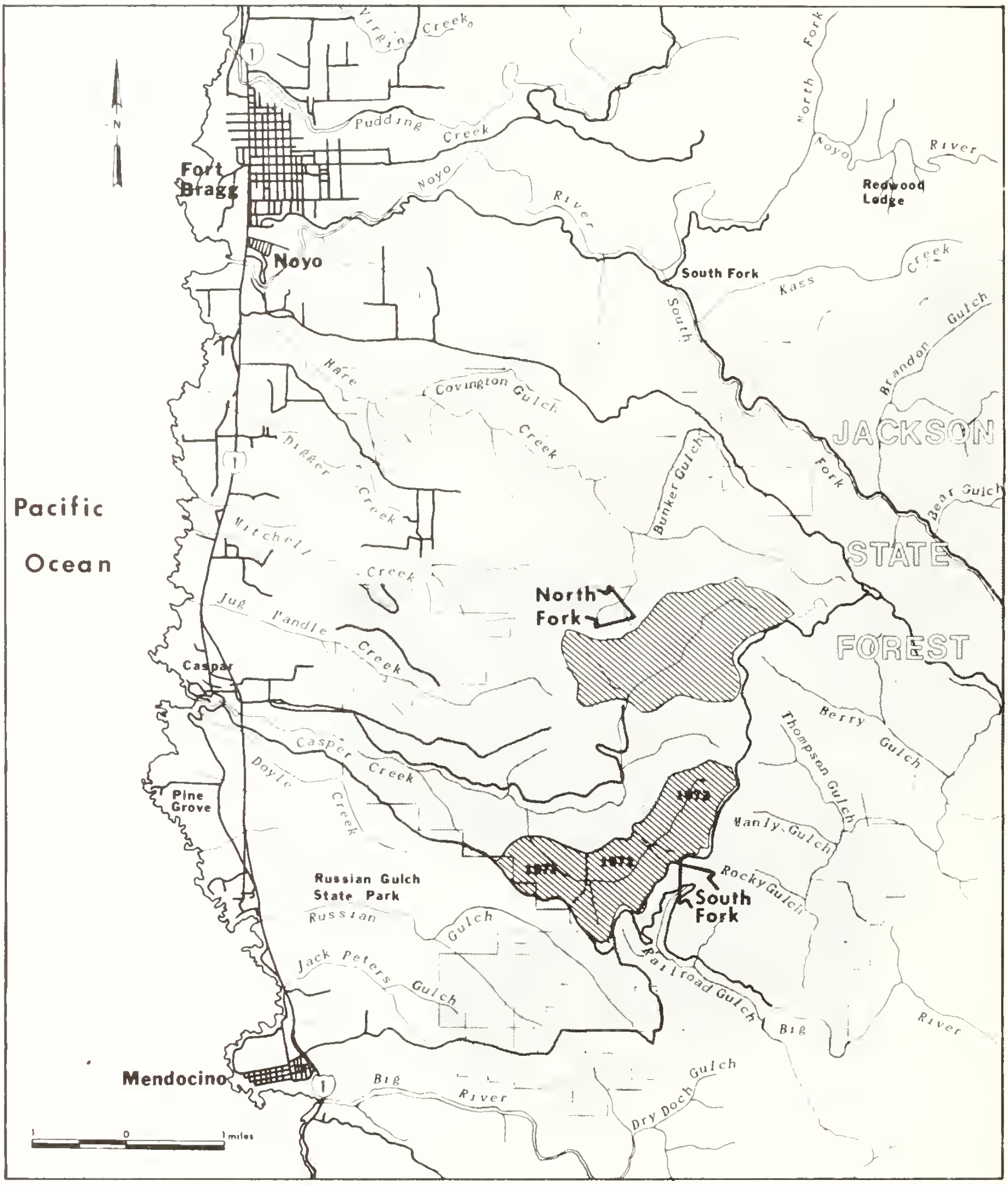


Figure 1—The two experimental watersheds, the North and South Forks of Caspar Creek, are on the Jackson State Forest, in northern California.

This paper offers a simple description of how road building and logging affect sedimentation. Field experiments are, however, rarely simple. Experimental results reflect not only the effects of conditions being tested, but also the vagaries of man and nature. In addition to the perturbations introduced into our data by weather patterns, malfunctioning instruments, and vandalism, our experiment included three other extraneous events of a less conventional nature.

A dam which had been storing sediment for 80 years failed in December 1967, the winter following road construction. During logging, one landing was constructed on an old landslide and subsequently produced exceptionally large amounts of erosion. During the winter after the completion of logging, a large landslide in the unlogged watershed yielded more sediment than measured in any 2 years in the rest of the study. Although these events complicated our analyses, we do not believe that any of them negate the general trends of our findings. As appropriate, in the various sections which follow, we will explain how each complication was dealt with in order to improve our interpretation of the results.

CASPAR CREEK WATERSHED

> **Jones' Law:** *Things are always more complicated than they have any right to be.*

The Caspar Creek Watershed Study is a joint investigation of the California Department of Forestry and the Pacific Southwest Forest and Range Experiment Station. It was planned as a traditional investigation of paired watersheds—one logged, one left alone *(fig. 1)*. After a period of calibration during hydrologic years 1963 through 1967, the main road network was constructed in the South Fork drainage *(table 1)*. During 1971-73, after the effects of road construction had been evaluated (Krammes and Burns 1973), the South Fork was selectively logged and the effects of the harvest monitored until the end of hydrologic year 1976. We are continuing to measure streamflow and sediment production from the two watersheds in anticipation of the next phase of the Caspar Creek Watershed Study, an evaluation of skyline logging which is planned to begin in 1984.

The North and South Forks of Caspar Creek have areas of 1225 acres (508 ha) and 1047 acres (424 ha) respectively; they are located about 7 miles (11 km) southeast of Fort Bragg, California. Soils are mainly Hugo or Mendocino, overlying sedimentary rocks of Cretaceous age. The climate is typical of the northern California coast, having mild summers with fog but little or no precipitation. The watersheds receive about 40 inches (1000 mm) of rainfall each year, concentrated in the months of October through April. Both watersheds were clearcut and burned in the late 1880's.

Table 1—*Details of timber harvest in the South Fork of Caspar Creek*

Item	Year logged					
	1967[1]	1971	1972	1973	Average	Total
Area logged (acres) (M bm)	47	249	316	435	—	1047
Total stand/acre	85.1	69.9	62.7	51.3	61.3	—
Harvest/acre (M bm)	85.1	41.4	43.0	33.1	39.2	—
Road construction (acres)	47	[2]5.0	[2]1.2	[2]1.7	—	54.9
Skid trails (acres)		21.7	27.6	38.0	—	87.3
Landing (acres)		8.7	3.3	9.0	—	21.0
Percent of logged area sampled in 1976	100	12.1	10.8	7.4	9.4	—

[1] Logging only for right-of-way clearing.

[2] Temporary road not included in road work described by Krammes and Burns (1973).

METHODS

Stephen's Law: *The stature of a science is often measured by the extent to which it utilizes mathematics.*

Streamflow

From the outset, the Caspar Creek investigation was aimed primarily at determining the influence that logging and road building might have on streamflow peaks and sediment loads. It was expected that increases, if any, in total water yield as a result of harvest would be of little importance in northwestern California. With this emphasis on peak flows and sediment, little effort was made to ensure that complete records of summer flows were obtained. The lack of complete summer records had two consequences. First, we were unable to determine if any water yield increases occurred because they are characteristically manifested as increased summer flows (Anderson and others 1976). Second, we had to reconstruct records in order to estimate annual suspended sediment loads. These reconstructions were based, in large measure, upon the performance of the companion watershed. This procedure may have induced a higher degree of correlation between the two catchments than exists in nature. The reconstructed data does not, we feel, seriously affect our analyses. Practically all the reconstructions apply to low flow periods during which a minute fraction of the total sediment load is transported, so the effect on annual loads would be minor.

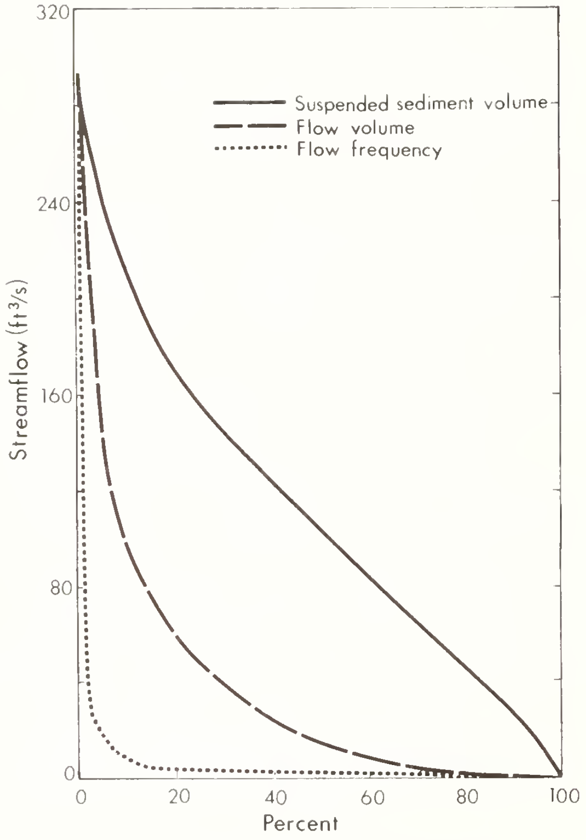


Figure 2—Flow and sediment regimes of South Fork Caspar Creek showing the percentage of the flow frequency, flow volume, and sediment volume occurring at higher discharges than the level indicated. For example: about 80 percent of the sediment transport takes place in flows greater than 40 ft³/s.

The flow regime of the South Fork is typical of many small forested watersheds in that for most of the time, flows are low relative to maximum discharges; most of the flow volume, and especially most of the sediment load, is carried during relatively brief periods of high discharges *(fig. 2)*. For example, discharges greater than 45 cu ft/s (1.27 m^3/s) occur approximately 1 percent of the time, but carry 26 percent of the volume of the water and 81 percent of the suspended sediment that is discharged annually by the stream. Recognition of these relationships led to the creation of a variable, $N\bar{Q}_{25}$, to index the year-to-year variability in sediment transport capability of the North Fork of Caspar Creek. $N\bar{Q}_{25}$ was the mean discharge rate of the flows which yielded the upper 25 percent of the flow volume of the North Fork. Throughout this paper, the term "stream power" will be used as a synonym for either $N\bar{Q}_{25}$ or the similar measurement in the South Fork, $S\bar{Q}_{25}$.

Suspended Sediment

Annual suspended sediment loads were estimated by multiplying the volume of flow in each of 19 discharge classes by the mean suspended sediment concentration in each of those classes and summing. Class boundaries were located so that approximately 5 percent of the annual flow occurred in each class. The weight of sediment thus computed was converted to a volume, assuming a factor of 74 pounds per cubic foot (1185 kg/m^3). As we had few data relating sediment concentration to steady or recession flows, our estimates of suspended sediment load had to be based on rising stage relationships. Because rising flows typically carry more sediment at a given discharge than recession flows, this compromise caused us to somewhat overestimate suspended sediment discharge of both the North Fork and the South Fork. The absolute increases in suspended sediment production as the result of logging or road building are therefore somewhat inflated, although the relative increases are likely to be near their true values. Because streamflow records were incomplete, about 0.02 percent of the streamflow record for discharges greater than 30 cu ft/s (0.85 m^3/s) was reconstructed. We are confident that neither of these compromises needed to estimate annual suspended sediment discharges had an appreciable effect on our results or conclusions.

During the calibration period (1963-67), a single composite sediment-discharge relationship was used to estimate annual suspended sediment loads for the South Fork of Caspar Creek. In subsequent years, while the South Fork was being disturbed by the effects of road building and logging, individual relationships were developing for each year. This procedure was used to guard against the possibility that the sediment-discharge relationship was changing from year to year. A single relationship was used throughout the study to estimate the suspended sediment load of the North Fork. This procedure differs from that of Krammes and Burns (1973), who used normalized suspended sediment discharges, after Anderson (1971). Consequently, our data differ from theirs for hydrologic years 1963-71.

Debris Basin Accumulation

The remainder of the sediment discharge was captured as deposits in the stilling ponds upstream from each of the Caspar Creek weirs. Annual accumulations were estimated by comparing bottom profiles of the sediment at approximately 24 cross sections in each of the reservoirs. When the reservoirs approached approximately one-half capacity, they were excavated during the summer season. On three occasions, this survey and cleanout procedure led to apparently illogical results—negative reservoir deposition during hydrologic years 1972 and 1976 *(table 2)*. These negative numbers may be the result of surveying errors; they may represent actual losses over the weir of remobilized bottom sediment; they may represent settling of the deposits or decay of organic material. Because all of the negative "accumulations" occur in dry years, we think the last explanation is the most probable. In either basin, less than 3 inches of settling could account for these differences. Assuming that a certain amount of compaction of sediment takes place in every year, we have chosen to use these negative numbers as our best estimates of the debris basin accumulations.

Calibration Equations

Two regression equations were computed in order to estimate the changes in sediment yield of the South Fork which may have resulted from road construction and logging. Each of the equations was based on two independent variables. The first independent variable was the estimated sediment discharge (either suspended sediment or debris basin accumulations) of the North Fork. The second variable was $N\bar{Q}_{25}$. The regressions were based on the relationships which existed during the calibration period (hydrologic years 1963-67). They were

$$SSF = 175 + 1.02\ SNF - 4.65\ N\bar{Q}_{25} \qquad (1)$$

$$DSF = 114 + .38\ DNF - 2.15\ N\bar{Q}_{25} \qquad (2)$$

in which

SSF = the annual suspended sediment discharge of the South Fork of Caspar Creek (yd^3/mi^2)

SNF = the suspended sediment discharge of the North Fork of Caspar Creek (yd^3/mi^2)

$N\bar{Q}_{25}$ = the mean discharge of the upper 25 percent of the flow volume of the North Fork of Caspar Creek (ft^3/s/mi^2)

DSF = the annual debris basin accumulation behind the South Fork weir (yd^3/mi^2)

DNF = the annual debris basin accumulation behind the North Fork weir (yd^3/mi^2)

Both the suspended sediment and the debris basin regression equations gave excellent fits to the data. They had coefficients of determination of 1.00 and 0.93, respectively.

Table 2—*Annual sedimentation and streamflow from the Caspar Creek watersheds*

	NORTH FORK				SOUTH FORK							
Hydrologic year	$\overline{NQ}_{25}$	Suspended sediment	Debris basin accumulation	Total sediment	$\overline{SQ}_{25}$	Suspended sediment: Observed	Suspended sediment: Predicted	Suspended sediment: Increase	Debris basin accumulation: Observed	Debris basin accumulation: Predicted	Debris basin accumulation: Increase	Total Increase
	Cu ft/s/sq mi	*Cu yd/sq mi*	*Cu yd/sq mi*	*Cu yd/sq mi*	*Cu ft/s/sq mi*	*Cu yd/sq mi*	*Cu yd/sq mi*	*Cu yd/sq mi*	*Cu yd/sq mi*	*Cu yd/sq mi*	*Cu yd/sq mi*	*Cu yd/sq mi*
Calibration period												
1963	24.50	101.15	56.32	157.45	24.68	160.94	164.30		87.04	82.64		
1964	30.23	94.00	64.00	158.00	33.84	130.28	130.35		44.80	73.24		
1965	68.36	612.54	685.44	1297.98	75.90	481.65	482.43		233.99	229.48		
1966	112.61	744.04	827.49	1571.53	110.84	411.30	410.90		193.27	188.63		
1967	24.30	138.24	60.16	198.40	24.73	206.90	203.09		109.44	84.55		
Total		1689.97	1693.41	3383.38		1391.07			658.54			
Average		337.99	338.68	676.68		278.21			131.71			
Road construction evaluation												
1968	20.99	67.65	53.76	121.41	28.06	547.03	146.42	400.61	133.77	89.22	44.55	445.16
1969	44.99	389.99	394.23	784.22	44.59	565.97	363.90	202.07	234.23	168.12	66.11	268.18
1970	52.93	387.21	227.19	614.40	50.14	312.15	324.18	−12.03	147.19	86.93	60.26	48.23
1971	67.51	490.09	371.82	861.91	79.83	596.28	361.37	234.91	418.54	111.00	307.54	542.45
Total		1334.94	1047.00	2381.94				825.56			478.46	1304.02
Average		333.74	261.75	595.49				[2]206.39			[1]119.62	[1]326.01
Logging evaluation												
1972	18.38	51.15	−80.00	−28.85	19.35	199.08	141.71	57.37	−149.75	43.52	−193.28	−135.91
1973	47.40	326.41	179.83	506.24	58.82	1894.91	287.78	1607.13	238.71	80.68	158.03	1765.16
1974	82.11	2707.48	1219.15	3926.63	93.43	2392.49	2554.82	−162.33	347.51	400.74	−53.23	−215.56
Adjusted[3]		601.15	573.51	1174.66			406.97	1985.52		156.99	190.52	2176.04
1975	48.89	393.01	238.07	631.08	41.20	1168.08	348.85	819.23	102.39	99.81	2.58	821.81
1976	22.78	52.81	−35.20	17.61	29.27	286.13	122.94	163.19	48.00	51.24	−3.24	159.95
Total		3530.86	1521.85	5052.71				2484.59			−89.14	2395.45
(Adjusted)[3]		(1424.53)	(876.21)	(2300.74)				(4632.44)			(154.61)	(4787.05)
Average		706.17	304.37	1010.54				[2]496.92			−17.83	[2]479.09
(Adjusted)[3]		(284.91)	(175.24)	(460.15)				[2](926.49)			[2](30.92)	[2](957.41)
Combined data-road construction and logging												
Total		4865.80	2568.85	7434.65				3310.15			389.32	3699.47
(Adjusted)[3]		(2759.47)	(1923.21)	(4682.68)				(5458.00)			(633.07)	(6091.07)
Average		540.64	285.43	826.07				[2]367.79			[1]43.26	[2]411.05
(Adjusted)[3]		(306.61)	(213.69)	(520.30)				[2](606.45)			[1](70.34)	[2](676.79)

[1] Increase statistically significant $p < 0.05$ level according to Chow's (1960) test.

RESULTS

Gumperson's Law: *The probability of anything happening is in inverse ratio to its desirability.*

Road Construction

The effects of road construction and logging were analyzed separately. Each of these analyses had two parts. Erosion was estimated to quantify the impact of the activity on the watershed and sediment increases were tested statistically to evaluate the response of the watershed to that impact.

Erosion

The main road in the South Fork of Caspar Creek was constructed during the summer of 1967. During the following December, an old splash dam failed in the South Fork drainage, about 300 feet (91 m) downstream from a major stream crossing of the road. The dam had been storing sediment for approximately 80 years since it was last used to flush logs downstream during the original logging of the South Fork. Krammes and Burns (1973) estimated that slightly in excess of 925 cu yd (707 m^3) of the 5600 cu yd (4282 m^3) of stored sediment were released. Although the exact cause of failure is not certain, we believe the road construction, and especially disturbance at the stream crossing, was probably responsible.

In addition to the erosion of splash dam sediment, Krammes and Burns (1973) estimated that about 650 cu yd (497 m^3) of erosion occurred on the road in the immediate vicinity of the stream channel. They acknowledged, however, having no estimate of the material eroded during the construction of the stream crossing or the amount that may have spilled into the stream during road maintenance, and make no mention of measurements of surface erosion on the road prism. Consequently, in our appraisal of the impact of road construction, we have chosen to consider that the splash dam failure and its sediment were entirely attributable to road construction. In this way we are compensating, in part, for the underestimation of road prism erosion which apparently occurred.

Sedimentation

Suspended sediment production during the winter following road construction was over 3.7 times that predicted (*fig. 3*). The amount of excess suspended sediment declined in hydrologic year 1969 and the observed sediment load in 1970 was below that predicted. Since about 2.4 miles (3.9 km) of the main road and 1.3 miles (2.1 km) of spur roads in the South Fork were within 200 feet (61 m) of the stream channel, we feel that this rapid decline in suspended sediment was to be expected. It agrees with the findings of Megahan (1974) in his studies of erosion following road construction in Idaho. In 1971, in response to high streamflow, suspended sediment observed in the South Fork rebounded to exceed that predicted by 65 percent.

Debris basin accumulations in the first year following road construction were about 50 percent greater than predicted (*fig. 3*). This increase persisted through 1969 and 1970. In 1971, the increase was more than four times the predicted value. This large increase is probably the result of two factors. First, flows in the South Fork that winter were high enough to have the ability to entrain incipiently unstable sediment throughout the stream channel. Second, the heavier fractions of splash dam sediment released in 1968, some 10,800 feet (3292 m) upstream from the debris basin, were finally reaching it.

In total, over the 4 years between road construction and the beginning of timber cutting, the South Fork watershed produced about 1304 cu yd/sq mi (385 m^3/km^2) excess sedimentation, which we attribute to the construction of approximately 3.7 miles (6.0 km) of logging roads in the riparian zone of the South Fork of Caspar Creek.

Logging

Erosion

Estimates of erosion were obtained from seven plots in the South Fork of Caspar Creek. Those plots were selected so as to sample the three ages of cutting and to be representative of the condition of the South Fork watershed. Measurement procedures were identical with a more general study of logging-related erosion in northwestern California (Datzman 1978) and very similar to methods used by the California Department of Forestry in a statewide study (Dodge and others 1976). The plots were rectangular, 10 chains (201 m) wide and from 10 to 16 chains (201 to 322 m) long, depending on the distance from which logs were being yarded to the landing. Within the plots, gullies greater

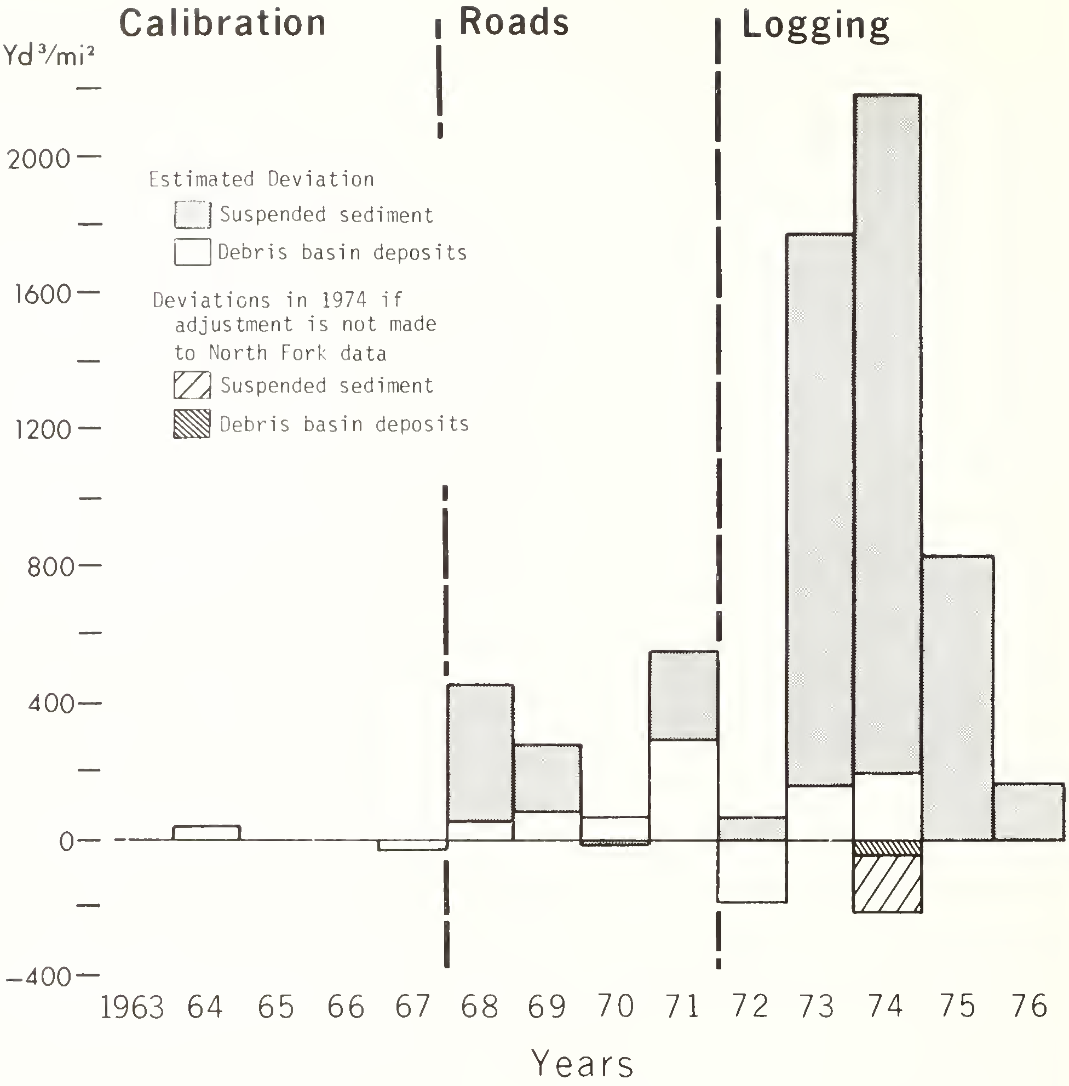


Figure 3—Deviations of sediment yield in the South Fork of Caspar Creek from the amount predicted from observations in the North Fork.

than 1 sq ft (0.09 m²) in a cross-section and mass movements displacing more than 1 cu yd (0.76 m³) of soil were completely measured. Ground conditions and minor erosional features were sampled on transects at 2-chain (40-m) intervals along the length of the plots. From these data we estimate that the timber harvest resulted in 42.9 cu yd/acre (81.1 m³/ha) excess erosion.

Sedimentation

The response of the South Fork watershed to the logging disturbance, though quite dramatic, must be considered together with the fact the post-harvest period included years of both very abundant and very deficient rainfall and runoff. Overwhelmingly, logging affected suspended sediment discharges *(fig. 3)* more than debris basin accumulation.

The stream power of both forks of Caspar Creek was lower in hydrologic year 1972 than in any other year in the study. This apparently resulted in a very small suspended sediment increase. The small increase also may be due, in part, to the fact that only 25 percent of the watershed had been logged the previous summer. During the following winter, with over one-half the watershed logged and somewhat above normal rainfall and stream power, suspended sediment loads were 6.6 times greater than predicted *(table 2)*.

Events during hydrologic year 1974 greatly complicated our efforts to estimate the effect that timber harvest was having on the suspended sediment discharge of the South Fork watershed. Two large landslides occurred adjacent to stream channels during a March storm. One was in the North Fork; one was in the South Fork. The North Fork slide, 4234 cu yd (3306 m^3), dumped much of its sediment directly into the stream, which transported it to the weir where it was measured. The South Fork slide, 727 cu yd (556 m^3), knocked down riparian trees and built itself a bridge above the stream. As a consequence, only a comparatively small portion of its total sediment had entered the stream by the end of the study. As a result of these two unusual events, a straightforward use of equation 1 leads to an estimated decrease in suspended sediment load in the South Fork for hydrologic year 1974. If the suspended sediment discharge in the North Fork is adjusted to its normal relationship with stream power *(fig. 4a)*, equation 1 leads to a more reasonable estimated increase in suspended sediment of almost six times the predicted value.

Suspended sediment increases, both in absolute and relative terms, decreased in hydrologic year 1975 and again in hydrologic year 1976. In total, suspended sediment production for the 5 years following the beginning of logging was 4.5 times greater than the amount predicted by the calibration equation.

Following the 1972 hydrologic year, surveys of the debris basins indicated negative accumulations in both the North Fork and the South Fork. As noted earlier, we elected to use these negative numbers together with equation 2 to estimate the effect of logging. That estimate, however, may be subject to large errors, as it was computed using values which were much beyond the range of the calibration data. In hydrologic year 1973, a modest increase in debris basin accumulation was estimated. In 1974, a similar increase was arrived at using adjustments similar to those used to estimate suspended sediment increases. From these data it appears that the effect of logging on suspended sediment is much greater than its effect on debris basin accumulations. It may be, however, that since the logging disturbances occurred farther from the weir than those associated with road construction, the heavier materials which would be measured as debris basin accumulation have yet to arrive at the weir. At this time there is no clear indication which interpretation is correct.

In summary, the effect of logging on sedimentation in the South Fork was mainly expressed as increases in suspended sediment discharge. Although the record was complicated by the events of 1972 and 1974, we have been able to adjust our estimates to overcome the difficulties presented. Using the adjusted predictions, we estimate a sediment increase of about 4787 cu yd/sq mi (1413 m^3/km^2). We feel that such an adjusted estimate is probably closer to the typical response to logging than one which would have resulted from the rigid use of the predisturbance regression equation with the observed data.

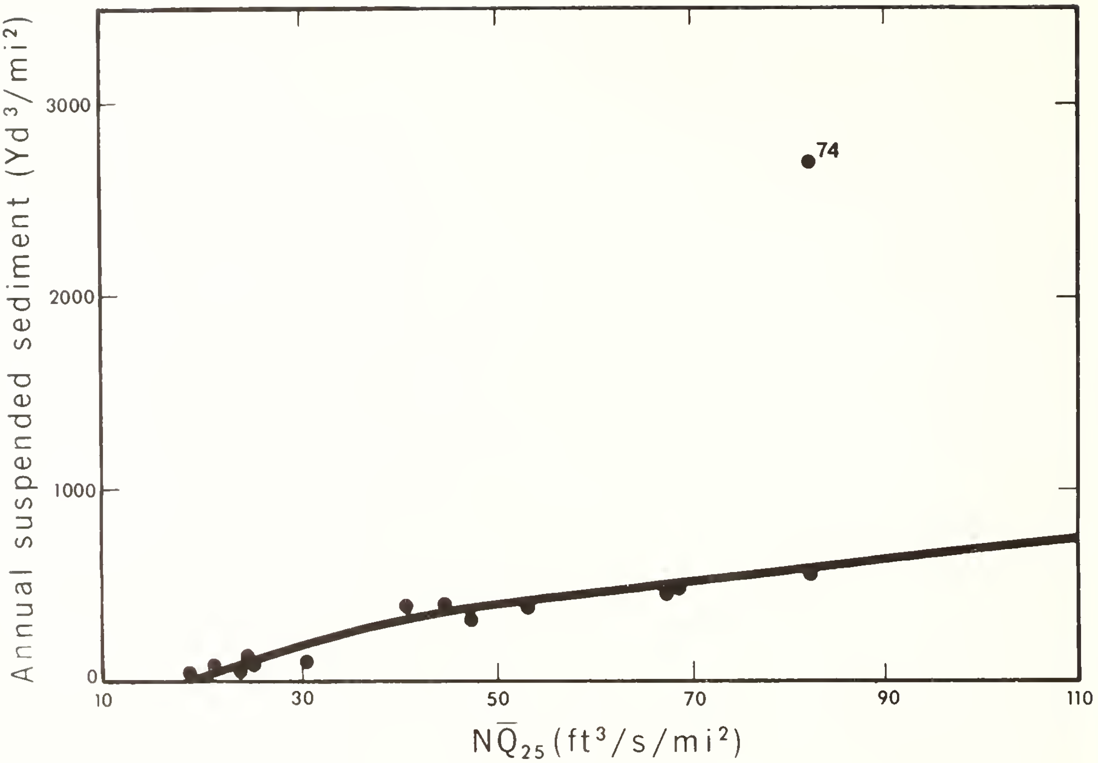
INTERPRETATIONS

Hoare's Law: *Inside every large problem are small problems struggling to get out.*

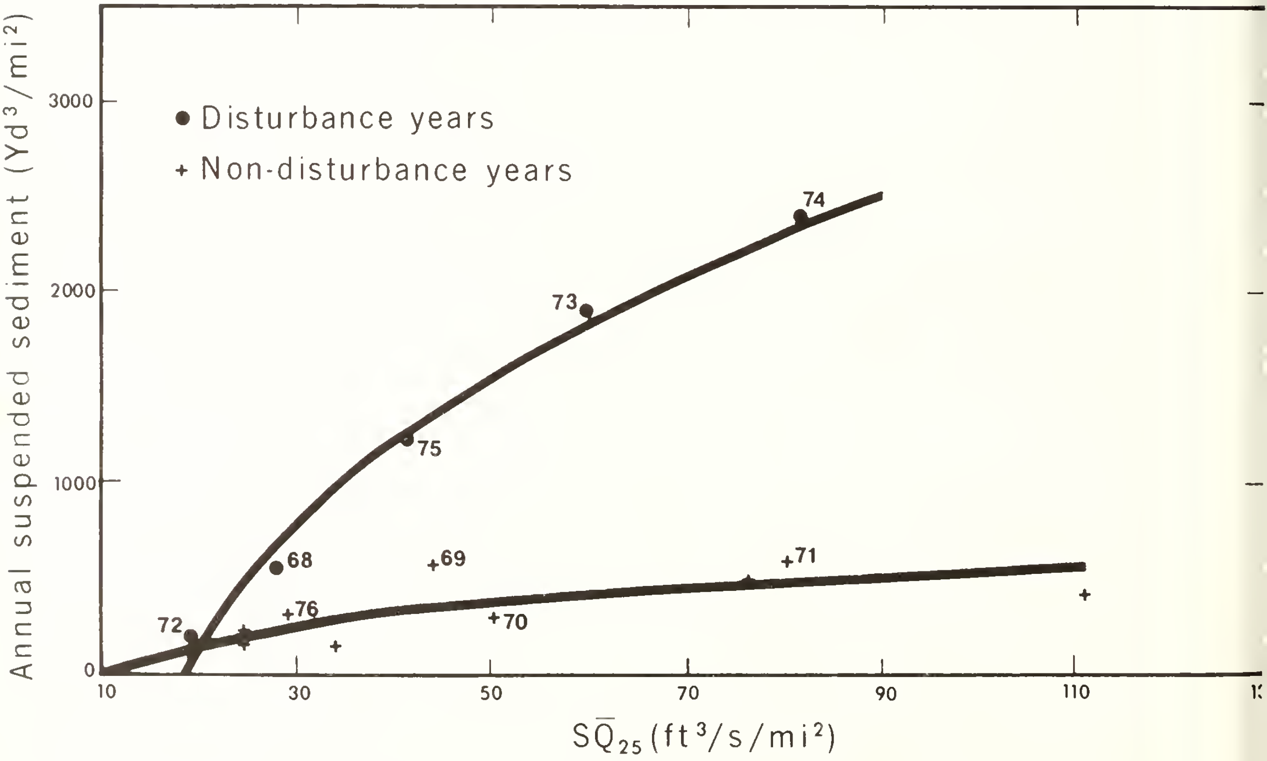
It is not enough to know that a particular logging operation had a particular effect on sedimentation. Other questions need to be answered, at least in part. What mechanisms have caused the observed changes in sedimentation? What might be the long-term implications of repeated management impacts such as those described here? How does this logging operation relate to others?

Mechanisms

Inspection of the South Fork's suspended sediment data suggests that the relationship between suspended sediment and stream power changed appreciably during some of the postcalibration years *(fig. 4b)*. The most marked differences were seen in the postlogging years of 1973-75, and only hydrologic year 1970 had a suspended sediment discharge lower than predicted by the calibration equation. The years that roadbuilding and logging began (1968 and 1972) also appear to fit the same curve as 1973-75, although the very low year of 1972 could be fitted to either curve. Since some suspended sediment increase in response to logging one quarter of a watershed would be expected, we have chosen to include 1972 with what we shall call the "disturbance" years (hydrologic years 1968, 1972-75). With the exception of the disturbance years, the relationship between suspended sediment and stream power in the South Fork is quite similar to that which exists in the North Fork *(fig. 4)*. Both watersheds show only a modest increase in suspended sediment load with increases in stream power. The disturbance years show a much different relationship. Suspended sedi-



a North Fork



b South Fork

Figure 4—Annual sediment discharge of the forks as related to stream power as indexed by $\bar{Q}_{25}$ (the mean discharge for the top 25 percent of the flow volume).

ment discharge increases markedly with increased stream power. We believe the two curves describe fundamentally different flow regimes. In the "nondisturbance" years, stream channels and the watershed surface are so stable that the stream has transporting power in excess of the available sediment. Consequently, this regime is *supply dependent*. During the disturbance years, on the contrary, a superabundance of transportable material is delivered to the drainage system. Sediment discharge is no longer determined solely by the availability of sediments; rather, it is mainly a function of the transporting ability of the stream. In this circumstance, the regime is *stream power dependent*. Debris basin accumulations also show a similar shift from supply dependence to stream power dependence, although not as dramatic as the shift for suspended sediment. It appears, then, that the principal effect that logging and roadbuilding have had is to deliver sediment to the stream.

Soil Loss

A fundamental question remains: What is the long term impact of roading and logging in the South Fork of Caspar Creek? To answer it, we need to distinguish between the estimated physical consequences of the operation and our professional and esthetic appraisals of it. In keeping with the Forest Practice Rules in existence at the time, relatively little consideration was given to erosion control or the control of water. Water bars were infrequently and inexpertly installed. Ephemeral channels were frequently used as skid trails, and landings were located with little regard to slope hydrology or slope stability. Four years after logging the scars had yet to heal. The measurable physical impacts were much less dramatic. The 10 percent of the watershed which had been severely disturbed by skid trails and landings *(table 1)* presumably may be less productive. Similarly, the 5 percent of the watershed now occupied by road prisms will yield few forest products. The road system, however, represents a necessary permanent investment in the management of the drainage. To the extent that landings and skid trails are reoccupied for later harvests, they too can be considered as necessary deductions from the area available to grow trees. Because the future utilization of the currently installed transportation network is uncertain, it is difficult for us to say how much of the land thus taken out of production was unnecessarily lost. Our best *guess* would be about 3 percent.

The average soil depth in the South Fork of Caspar Creek is about 4 feet (1.2 m). Assuming that the measured "erosion" represents the excess loss of soil from the site for each harvest (that is, natural erosion equalled replenishment from natural soil genesis), and assuming that similar disturbances would occur at approximately 50-year intervals, the soil resource would be totally exhausted in about 7900 years *(table 3)*. Our sedimentation data, however, indicate that only about

Table 3—*Short- and long-term impacts of logging and road construction in the South Fork of Caspar Creek*

Disturbance	Delivery ratio	Soil lost due to disturbance				Estimated time for complete removal of soil mantle[2]	
		Volume		Proportion of soil mantle[1]			
		Erosion	Sedimentation	Erosion	Sedimentation	Erosion	Sedimentation
		Cu yd/sq mi		*Percent*		*Years*	
Road construction	1.35	962.75	1,304.02	0.0233	0.0316	214,497	158,362
Logging, observed	.091	26,221.75	2,395.45	.635	.0580	7,875	86,208
Logging, adjusted[3]	.183	26,221.75	4,787.05	.635	.116	7,875	43,046
Total, observed	.136	27,184.50	3,699.47	.658	.0896	7,596	55,821
Total, adjusted[3]	.224	27,184.50	6,091.07	.658	.148	7,596	33,903

[1] Assumes a soil depth of 4 feet.

[2] Assumes that similar impacts occur at 50-year intervals and that new soil forms during the period at a rate equal to natural erosion.

[3] Adjusted by using the normal sedimentation of the North Fork for 1974 rather than the observed rate resulting from the landslide.

22 percent of the eroded material has left the watershed. Using sediment volume with similar assumptions, we estimate the soil would not be exhausted for 33,900 years. Clearly, both of these figures, which include stringent and unfavorable assumptions of repeated *equal* impacts and no increased rate of soil formation, represent planning horizons much beyond what a forest manager must consider. It might be argued that our calculations underestimate site degradation, because erosional processes will remove a disproportionate share of the more fertile surface layers of the soil. Undoubtedly, this is true to some extent; however, our erosion measurements recorded only 3 percent of the total erosion as rill erosion. The remainder occurred as landslides or large gullies which remove mainly the less fertile subsoil. Although we are not advocating unnecessary erosion, these inferences and extrapolations from our data would suggest that timber harvest, such as we measured in the South Fork, would not cause unacceptable site damage.

Water Quality

In any appraisal of forest management impacts, water quality is a major concern. The implications of our estimates are more gloomy here. Although the first and fourth largest South Fork discharges occurred during the 5-year calibration period, suspended sediment loads during 6 of the 9 postcalibration years exceeded any recorded in the South Fork while it was undisturbed. With similar disturbances and 50-year intervals assumed, it is doubtful that the aquatic ecosystem can maintain itself when perhaps 10 percent of the years in each century are above the normal range of variability. In addition to possible ecological impacts, forest managers need to consider the legal restraints on water quality degradation. If turbidity changes have paralleled suspended sediment changes, as we would expect, in 8 of 9 postcalibration years turbidity exceeded the standards of the North Coast Regional Water Quality Control Board (no increases greater than 20 percent above background). We may now ask, which is at fault, the logging and roadbuilding methods or the water quality standards? The new Forest Practice Rules may be expected to reduce considerably the amount of water pollution which may result from timber harvest. It appears unlikely, however, that even operations totally in keeping with the Forest Practice Rules will avoid all turbidities in excess of 20 percent above background. Therefore, it might be more prudent to modify water quality standards so that they specify more attainable goals.

Comparison to Other Logging

Fortunately, information that allows appraisal of the "representativeness" of the Caspar Creek Study is available from an investigation of erosion of logged areas in northwestern California (Datzman 1978). This study included 102 plots stratified so as to sample as many combinations of important site variables as possible. The seven Caspar Creek plots were compared with two groups of plots from Datzman's data. Both groups were composed of plots which had been logged at about the same time as Caspar Creek, and which had supported second-growth timber ("second-growth" includes all plots other than old-growth redwood). One group of plots was composed of partial cuts and the other included plots which had been tractor yarded.

Our comparisons were based on two erosion variables, 14 site variables, and 12 surface condition variables *(table 4)*. The Caspar Creek plots were most like the other four partially cut plots, with respect to site and surface condition variables, and none of the differences between the Caspar Creek plots and the 14 tractor-yarded plots appears serious. Comparison of the erosion variables shows obvious important differences. Caspar Creek appears to have experienced significantly more erosion and possibly higher values of the variable Net Soil Loss as well. Seeking an explanation, we found that the landing at one of the Caspar Creek plots had been located on the toe of an incipient unstable rotational failure. When the predictable slump occurred, it yielded almost one-half of the erosion measured in Caspar Creek.

Had ours been the only observation of a data set being dominated by an extreme event, we might have had serious reservations about the "representativeness" of the Caspar Creek experiment. It appears, however, that such domination may be common. Datzman's (1978) data are dominated by five large events and another large data set of road-related erosion is dominated by three. Consequently, although we might prefer the data to be well behaved, it probably represented the sort of random perturbations to be found in most investigations of erosion. Thus, we believe that the *interim* use of Caspar Creek as a prototype for logging impacts in second-growth tractor harvest of timber in northwestern California is warranted. Another reason for this position is that we, like Froelich (1973), believe that the most important determinant of erosion and disturbance is not variation in site conditions, but differences in operator performance—the mistakes that led to erosion in Caspar Creek could be made on future timber harvests.

Table 4—*Characteristics of logged plots in Caspar Creek watershed study and of other second-growth plots (comparable with respect to time elapsed since logging) in northwestern California*

Characteristic	South Fork Caspar Creek	Partially cut plots[1]	Tractor yarded plots[2]
Plots (number)	7	4	14
Area sampled (acres)	94	44	164
Erosion variables (yd^3/acre):			
Erosion[3]	42.9	10.6	8.3
Net soil loss[3]	150.9	90.0	134.1
Site variables:			
Age since logging (yr)	3.86	4.75	4.50
Mean annual precipitation (in)	44.29	61.25	67.50
10 yr maximum 24 hr (in)	4.56	6.42	6.81
2 yr maximum 6 hr (in)	1.80	2.10	2.16
Aspect severity[4]	5.29	4.75	4.50
Slope (pct)	29.7	31.0	38.5
Elevation (ft)	634	1638	1936
Sand in surface soil (pct)	58.6	51.6	50.2
Clay in surface soil (pct)	17.7	19.3	21.7
Sand in subsurface soil (pct)	43.7	55.4	50.7
Clay in subsurface soil (pct)	29.4	19.9	22.7
Field aggregate stability[5]	4.34	5.10	5.43
Lab. aggregate stability surface[6]	31.2	36.8	42.4
Lab. aggregate stability subsurface[6]	45.9	35.0	41.6
Surface condition variables:			
Area in roads (acres)	0.149	0.298	0.249
Area in landings (acres)	.281	.223	.349
Area in skid trails (acres)	1.43	1.12	1.26
Bare ground (pct)	7.9	12.0	21.4
Slash (pct)[7]	20.6	14.8	16.2
Litter (pct)[7]	27.6	22.2	18.3
Wood (pct)[7]	7.1	11.8	10.7
Herbaceous plants (pct)	13.3	13.5	8.4
Shrubs (pct)	2.9	17.8	15.1
Conifers (pct)	16.6	4.8	2.6
Hardwoods (pct)	3.4	3.0	2.4
Rock (pct)	0.9	1.3	5.4

[1] Includes both cable and tractor yarding.

[2] Includes both partial cuts and clearcuts.

[3] Erosion included all mass failures, all gullies with cross-sectional area greater than 1 ft^2, and rills (based on transect sampling) with cross-sections greater than 0.1 ft^2. Erosion + excavation − fill = net soil loss.

[4] Rated on a scale from 1 (N) to 8 (S).

[5] Rated on a scale of decreasing stability from 1 to 10 (Calif. Reg., For. Serv. 1968).

[6] Represents the ratio of hydrometer readings after final time period in dispersed and aggregated suspensions.

[7] Slash is organic debris between 0.5 inches and 6 inches in diameter. Litter is smaller material and wood is larger.

CONCLUSIONS

Weinberg's Sixth Law: *If you never say anything wrong, you never say anything.*

In summary, we conclude that the study of roading and selective timber harvest in the watershed of the South Fork of Caspar Creek suggests that

- The watershed appears representative of other harvested areas investigated in northwestern California.
- The information gained in this study applies most directly to tractor-yarded, partially cut second-growth redwood and old-growth timber of other species.
- Disturbances from roadbuilding and logging changed the sediment/discharge relationship of the South Fork from one which was supply dependent to one which was stream power dependent, resulting in substantial increases in suspended sediment discharges.
- Although roadbuilding and logging apparently increased debris basin deposits as well, the nature of the increase is much less clear. Lags in the movement of bed material through the stream system may be the confusing element.
- The overall effect on site quality, as estimated by erosion or sedimentation, does not appear to be a cause for concern.
- Road construction and logging appear to have resulted in increases in average turbidity levels (as inferred from suspended sediment increases) above those permitted by Regional Water Quality Regulations.

LITERATURE CITED

Anderson, Henry W.
1971. **Relative contributions of sediment from source areas and transport processes.** In Proc. Symp. Forest Land Uses on Stream Environment, Corvallis, Oreg. 1970:55-63.

Anderson, Henry W., Marvin D. Hoover, and Kenneth G. Reinhart
1976. **Forests and water: Effects of forest management on floods, sedimentation, and water supply.** USDA Forest Serv. Gen. Tech. Rep. PSW-18, 115 p., illus. Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif.

California Region, Forest Service
1968. **Erosion hazard rating surveys.** FSM Supp. 62, Forest Serv. 2456.1—1 to 2456.6—4, U.S. Dep. Agric., San Francisco, Calif.

Chow, Gregory C.
1960. **Tests of equality of sets of coefficients in two linear regressions.** Econometrica. 28(3):591-605.

Datzman, Patricia A.
1978. **The erosion hazard rating system of the coast forest district. How valid is it as a predictor of erosion and can a better prediction equation be developed?** M.S. thesis, Humboldt State Univ., Arcata, Calif.

Dodge, Marvin, L.T. Burcham, Susan Goldhaber, Bryan McCulley, and Charles Springer
1976. **An investigation of soil characteristics and erosion rates on California forest lands.** Calif. Resour. Agency, Dep. For., 105 p.

Froelich, H.A.
1973. **Natural and man-caused slash in headwaters streams.** Loggers Handbook 33:15-17, 66-70, 82-86. Pac. Logging Congr., Portland, Oreg.

Krammes, J.S. and David M. Burns
1973. **Road construction on Caspar Creek watersheds . . . a 10-year progress report.** USDA Forest Serv. Res. Paper PSW-93, 10 p. Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif.

Megahan, Walter F.
1974. **Erosion over time on severely disturbed granitic soils: a model.** USDA Forest Serv. Res. Paper INT-156, 14 p., illus. Intermountain Forest and Range Exp. Stn., Ogden, Utah.

Rice, Raymond M., Forest B. Tilley, and Patricia A. Datzman.
1979. **A watershed's response to logging and roads: South Fork of Caspar Creek, 1967-76.** Res. Paper PSW-146, 12 p., illus. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

The effect of logging and roadbuilding on erosion and sedimentation are analyzed by comparing the North Fork and South Fork of Caspar Creek, in northern California. Increased sediment production during the 4 years after road construction was 326 cu yd/sq mi/yr—80 percent greater than that predicted by the predisturbance regression analysis. The average sediment load during the 3 years of logging increased by 957 cu yd/sq mi/yr—275 percent greater than the predicted values. Although the erosion or sediment increases do not appear to be degrading site quality, average turbidity levels in the South Fork exceeded water quality standards.

Retrieval terms: Selective logging, forest roads, regression analysis, suspended sediment, debris basin deposits, erosion, sedimentation, soil disturbance.

Rice, Raymond M., Forest B. Tilley, and Patricia A. Datzman.
1979. **A watershed's response to logging and roads: South Fork of Caspar Creek, 1967-76.** Res. Paper PSW-146, 12 p., illus. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

The effect of logging and roadbuilding on erosion and sedimentation are analyzed by comparing the North Fork and South Fork of Caspar Creek, in northern California. Increased sediment production during the 4 years after road construction was 326 cu yd/sq mi/yr—80 percent greater than that predicted by the predisturbance regression analysis. The average sediment load during the 3 years of logging increased by 957 cu yd/sq mi/yr—275 percent greater than the predicted values. Although the erosion or sediment increases do not appear to be degrading site quality, average turbidity levels in the South Fork exceeded water quality standards.

Retrieval terms: Selective logging, forest roads, regression analysis, suspended sediment, debris basin deposits, erosion, sedimentation, soil disturbance.

Rice, Raymond M., Forest B. Tilley, and Patricia A. Datzman.
1979. **A watershed's response to logging and roads: South Fork of Caspar Creek, 1967-76.** Res. Paper PSW-146, 12 p., illus. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

The effect of logging and roadbuilding on erosion and sedimentation are analyzed by comparing the North Fork and South Fork of Caspar Creek, in northern California. Increased sediment production during the 4 years after road construction was 326 cu yd/sq mi/yr—80 percent greater than that predicted by the predisturbance regression analysis. The average sediment load during the 3 years of logging increased by 957 cu yd/sq mi/yr—275 percent greater than the predicted values. Although the erosion or sediment increases do not appear to be degrading site quality, average turbidity levels in the South Fork exceeded water quality standards.

Retrieval terms: Selective logging, forest roads, regression analysis, suspended sediment, debris basin deposits, erosion, sedimentation, soil disturbance.

Rice, Raymond M., Forest B. Tilley, and Patricia A. Datzman.
1979. **A watershed's response to logging and roads: South Fork of Caspar Creek, 1967-76.** Res. Paper PSW-146, 12 p., illus. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

The effect of logging and roadbuilding on erosion and sedimentation are analyzed by comparing the North Fork and South Fork of Caspar Creek, in northern California. Increased sediment production during the 4 years after road construction was 326 cu yd/sq mi/yr—80 percent greater than that predicted by the predisturbance regression analysis. The average sediment load during the 3 years of logging increased by 957 cu yd/sq mi/yr—275 percent greater than the predicted values. Although the erosion or sediment increases do not appear to be degrading site quality, average turbidity levels in the South Fork exceeded water quality standards.

Retrieval terms: Selective logging, forest roads, regression analysis, suspended sediment, debris basin deposits, erosion, sedimentation, soil disturbance.

ates
nt of
e

vice

uthwest
d Range
nt Station

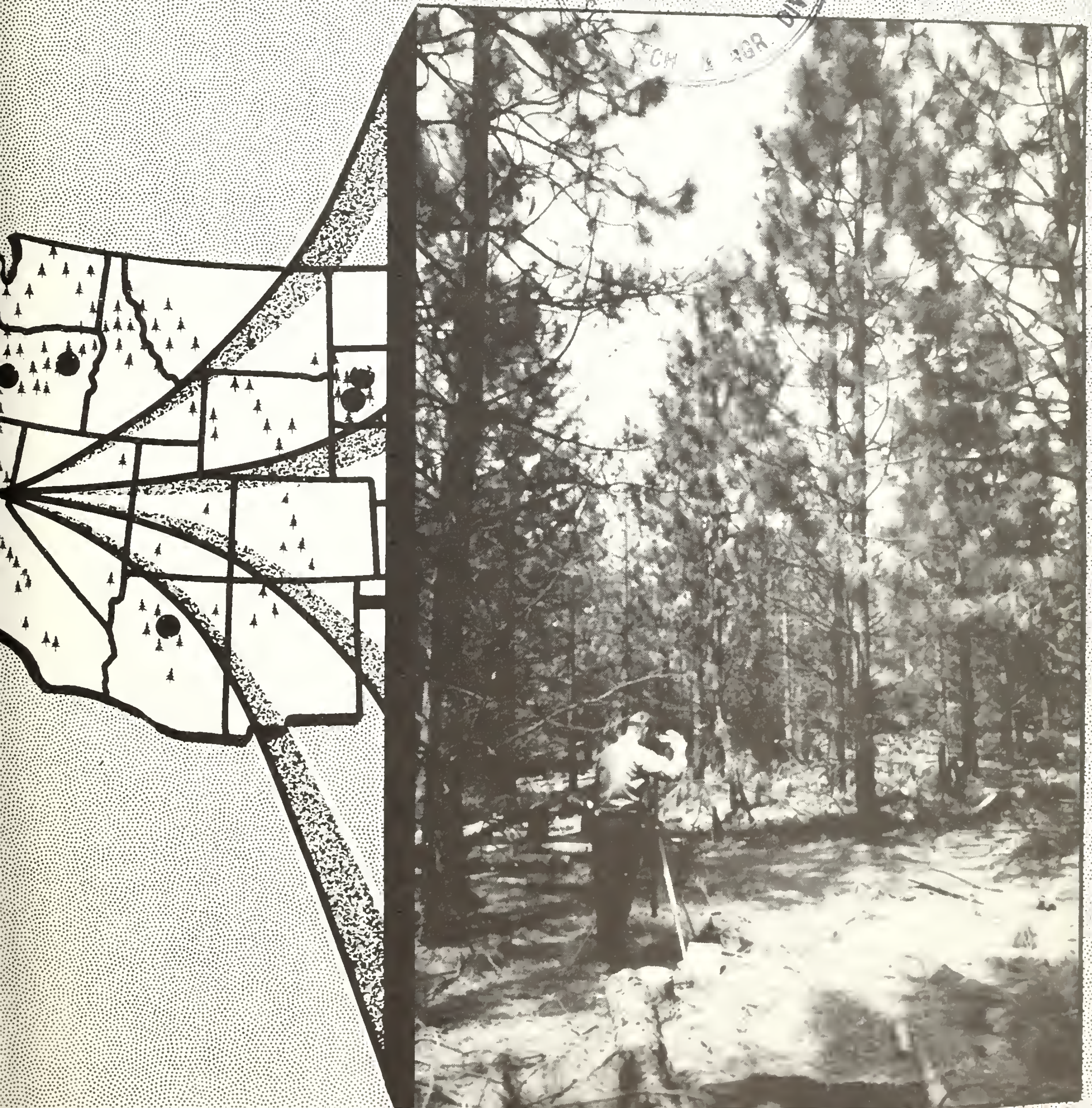
Paper

Growth of Planted Ponderosa Pine Thinned to Different Stocking Levels in Northern California

William W. Oliver

GOVT. DOCUMENTS
DEPOSITORY ITEM
APR 10 1980
CLEMSON
LIBRARY

CLEMSON UNIVERSITY LIBRARY
APR 11 1980
TECH & AGR. DIV.



The Author

WILLIAM W. OLIVER is doing silvicultural research on Sierra Nevada conifer types, with headquarters at Redding, California. He earned a B.S. degree (1956) in forestry from the University of New Hampshire, and an M.F. degree (1960) from the University of Michigan. A native of Pennsylvania, he joined the Station in 1962, after working for the Michigan Department of Natural Resources.

Cover: Growing-stock levels of ponderosa pine are being studied in four states: Cascade Range and Blue Mountains of Oregon, Black Hills of South Dakota, Colorado River Plateau of Arizona, and Sierra Nevada of California.

Growth of Planted Ponderosa Pine Thinned to Different Stocking Levels in Northern California

William W. Oliver

CONTENTS

Page

Introduction 1

The Elliot Ranch Plantation 1

Methods 2

Growth Related to Stocking Level 4

  Diameter 4

  Basal Area 8

  Height 8

  Crowns 8

  Volume 8

Damage and Mortality 9

Conclusions 10

Literature Cited 10

Pacific Southwest Forest and Range Experiment Station
P.O. Box 245
Berkeley, California 94701

September 1979

PREFACE

Growth of the most widely distributed pine in North America is under joint study by the western Forest and Range Experiment Stations of the Forest Service, U.S. Department of Agriculture. This west-wide study of growing-stock levels in even-aged ponderosa pine is in response to increasing demands for better and more precise estimates of yields possible in intensively managed stands.

This paper reports 5-year results from one installation in a plantation on the west slope of the Sierra Nevada of California. Reports from installations in naturally regenerated stands—two each in the Black Hills of South Dakota and central Oregon and one in northern Arizona—will be issued periodically, followed by a report summarizing results from all six installations.

Previous publications on this study are:

Myers, Clifford A.
1967. **Growing stock levels in even-aged ponderosa pine.** U.S. Forest Serv. Res. Paper RM-33, 8 p., illus. Rocky Mountain Forest and Range Exp. Stn., Fort Collins, Colo.

Schubert, Gilbert H.
1971. **Growth response of even-aged ponderosa pines related to stand density levels.** J. For. 69 (12):857-860, illus.

Schubert, Gilbert H.
1974. **Silviculture of southwestern ponderosa pine: The status of our knowledge.** USDA Forest Serv. Res. Paper RM-123, 71 p., illus. Rocky Mtn. Forest and Range Exp. Stn., Fort Collins, Colo.

Schubert, Gilbert H.
1976. **Silvicultural practices for intensified forest management.** In **Trees—The renewable resource. Proc. Rocky Mtn. For. Ind. Conf.** [Tucson, Ariz., March, 1976], p. 37-54.

Severson, Kieth E., and Charles E. Boldt.
1977. **Options for Black Hills forest owners: timber, forage, or both.** Rangeman's J. 4(1):13-15, illus.

IN BRIEF

Oliver, William W.
1979. **Growth of planted ponderosa pine thinned to different stocking levels in northern California.** Res. Paper PSW-147, 11 p., illus. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

Retrieval Terms: Pinus ponderosa, stand density-growth, diameter growth, basal area growth, volume growth, stocking level, plantation, California.

In California, most of the highly productive ponderosa pine (*Pinus ponderosa* Laws.) stands are found in plantations at mid-elevations on the west slopes of the Sierra Nevada and Cascade Ranges. But growth rates and their relationship to stand density are less known for these high sites than they are for less productive sites to the east. This paper reports remarkable growth for 5 years after thinning ponderosa pine in the Elliot Ranch Plantation to a wide range of stocking levels on a productive site.

The plantation lies at 4000 feet (1220 m) elevation, 11 miles (18 km) northeast of Foresthill, Placer County, California. Abundant precipitation (60 inches or 1524 mm annually), mild temperatures, and deep clay-loam soils provide favorable growing conditions. The Site Index is estimated to be 115 feet (35 m) at 50 years (Powers and Oliver 1978).

In spring 1950, following a wildfire the previous year that burned a brush and snag field, ponderosa pine was hand-planted at a 6- by 8-foot (1.8- by 2.4-m) spacing. Deerbrush (*Ceanothus integerrimus* H. and A.) germinated abundantly, but was held in check by cattle browsing. By 1969, when the study began, the plantation completely dominated the deerbrush understory.

Five growing-stock levels (GSL's) are being tested—40, 70, 100, 130, and 160. The GSL's are the basal areas in square feet per acre that the stand has, or will have, after thinning when the stand diameter averages 10 inches (25.4 cm) or more (Myers 1967). Treatments were replicated three times and assigned at random to 15 one-half acre (0.2 ha) plots. Trees were marked and the plots precommercially thinned in late 1969 when the plantation was 20 years old. Trees were measured the following spring before growth began and remeasured after five growing seasons.

Periodic annual growth in diameter was influenced strongly by growing stock level. Trees in plots heavily thinned to GSL 40 grew most rapidly at the annual rate of 0.51 inch (1.3 cm). Annual diameter growth declined rapidly with increasing stand density, then decreased to an annual rate of 0.21 inch (0.5 cm) for trees in plots lightly thinned to GSL 160. Surprisingly, only trees in plots heavily thinned to GSL 40 (and briefly in GSL 70) grew faster in diameter after thinning than these same trees grew before thinning. Trees in less heavily thinned plots continued their pattern of slackening diameter growth, begun before thinning.

Basal area growth was linearly related to stand density. Tree growth was 4.7 square feet per acre (1.1 m^2/ha) annually for GSL 40, increasing to 9.0 square feet per acre (2.1 m^2/ha) annually for GSL 160.

Overall, the average tree grew 1.9 feet (0.6 m) annually in height during the 5 years since thinning. Trees in plots at higher GSL's tended to grow more slowly than trees at lower GSL's, but differences were not significant.

Tree crowns were long (live crown ratio of 70 percent) when the plantation was thinned. Since thinning, all live crown ratios have decreased, especially at higher stand densities.

Total stem volume production from ground line to tip was impressive in these fully crowned trees. Volume production rose steadily with increasing growing stock levels from 116 cubic feet per acre (8.1 m^3/ha) for GSL 40 to 255 cubic feet per acre (17.8 m^3/ha) for GSL 160. In terms of compound interest, production ranged from 14 percent for GSL 40 to 10 percent for GSL 160.

Tree damage and mortality have been minor influences on stand growth. The most important agent—a heavy, wet snowfall in the winter of 1970 spacing in the ashes within which deerbrush seeds were germinating abundantly.

During the early years of the Elliot Ranch Plantation, the Tahoe National Forest evaluated cattle browsing as a method of controlling deerbrush (Sindel 1963). In the first year, before management procedures were perfected, cattle browsed over 90 percent of the pines, but few were killed. Since then, cattle use has remained heavy; but by removing cattle by September 15 each year, cattle have ignored the trees while browsing heavily on deerbrush.

Another fire, in August 1960, devastated 45,000 acres (18,225 ha) completely surrounding the Elliot Ranch Plantation. Small spot fires, less than 50 feet (15 m) in diameter and originating from burning snags, killed or scarred a few plantation trees. The plantation otherwise escaped unharmed.

By 1969, when the study began, trees completely dominated the deerbrush understory. Basal area averaged 155 square feet per acre (35 m^2/ha) and occasionally exceeded 300 square feet per acre (69 m^2/ha). The average tree was 7.0 inches (17.8 cm) d.b.h. *(table 1)* and 33 feet (10.1 m) tall.

Table 1—*Stand characteristics per acre before thinning a 20-year-old ponderosa pine plantation on a productive site to five growing stock levels*

Growing stock level[1]	Plot no.	Total trees	Average d.b.h.	Basal area
			Inches	*Sq. ft.*
40	13	487	8.2	177
	10	836	6.3	182
	8	719	6.5	165
70	15	486	7.4	147
	7	592	7.0	160
	5	509	7.2	143
100	14	426	7.7	138
	6	582	6.9	150
	1	493	7.0	133
130	11	509	8.0	178
	4	576	6.9	149
	2	533	6.5	122
160	12	620	7.0	164
	9	814	5.8	151
	3	583	7.1	160

[1] Stand density expressed as the basal area per acre that will remain after thinning when average stand diameter is 10 inches or more.

METHODS

The Elliot Ranch Plantation is part of a westwide growing-stock-levels study in even-aged ponderosa pine (Myers 1967). From a common study plan, each installation evaluates growth response to thinning in stand sizes growing on site qualities common to each region. Each installation is scheduled to run for 20 years, with measurements at 5-year intervals.

At Elliot Ranch, the five growing stock levels (GSL's) under test are 40, 70, 100, 130, and 160 *(fig. 1)*. These GSL's are the basal areas in square feet per acre that the stand has—or will have—after thinning, when the stand diameter averages 10 inches (25.4 cm) or more. The actual basal area after thinning stands less than 10 inches can be determined from *figure 2*. Each growing stock level was replicated three times. Treatments were assigned at random to 15 one-half acre (0.2 ha) plots. Trees were marked and the plots precommercially thinned in fall and winter 1969 when the plantation was 20 years old.

Thinning this stand of large poles precommercially generated huge volumes of slash. In plots heavily thinned to GSL's 40, 70, and 100, slash was eliminated to lessen fire hazard and reduce chances of insect attack. Tops and limbs of all felled trees were piled and burned, often within the plots. Where slash volumes were light (GSL's 130 and 160), slash was lopped and scattered. Tree boles in every plot were bucked into 6- to 8-foot (1.8- to 2.4-m) lengths; in the following fall, those easily accessible were removed by fuelwood gatherers.

Before growth began in the following spring, all trees were tagged, were described by crown class, and were measured for d.b.h. to the nearest 0.1 inch (0.25 cm). Tree damage and diseases were noted. Also, 20 percent of the trees, randomly chosen in each plot, were measured to the nearest foot (0.3 m) for total height, crown width, and crown length. Stem volumes were measured on six trees per plot. Selection probability for this sample was proportional to estimated cubic volume. Upper stem diameters and lengths were measured by an optical dendrometer.

All measurements were repeated on the same trees after five growing seasons *(fig. 3)*. Increment cores also were extracted from 8 percent, or not less than five trees, randomly selected in each plot, for estimating annual diameter growth. Ring widths were measured back to 1965 to determine diameter

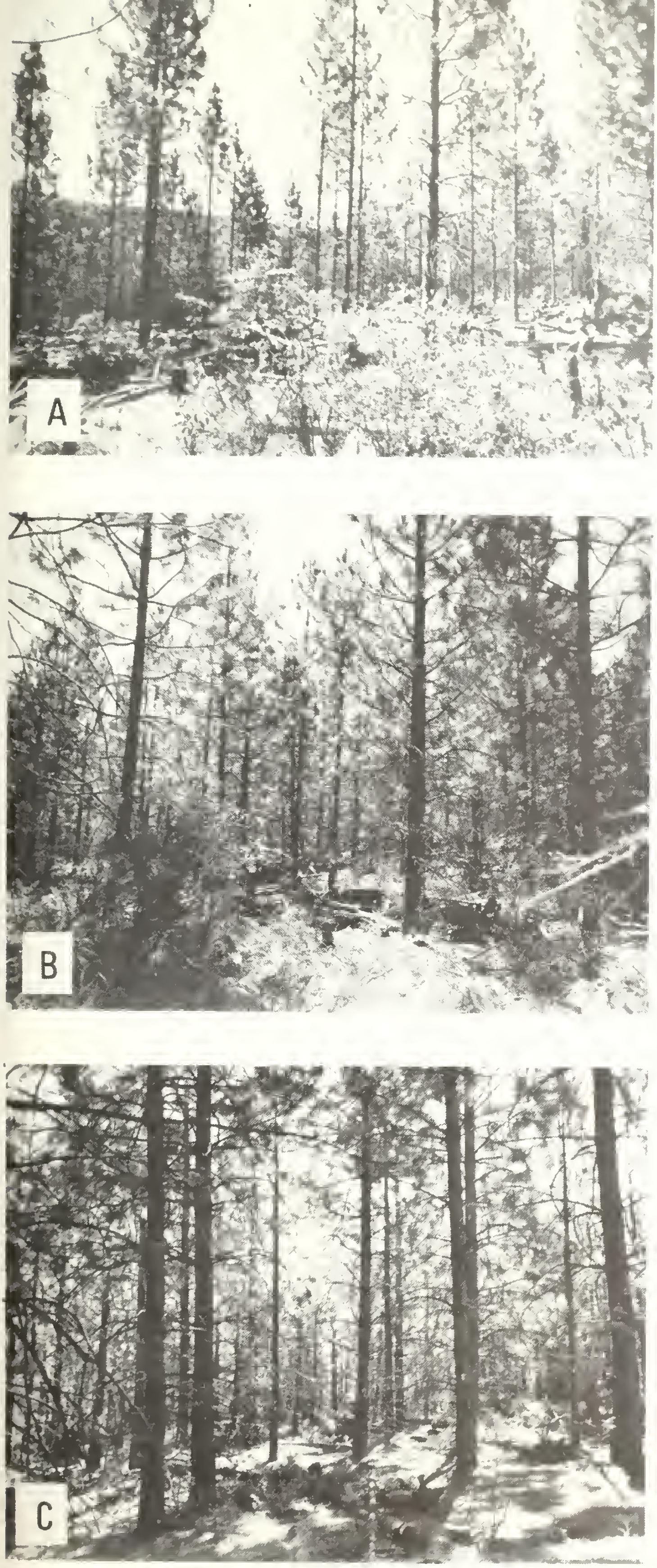


Figure 1—The Elliot Ranch Plantation was thinned at 20 years of age to five different growing stock levels (GSL), including *(A)* GSL 40, *(B)* GSL 100, and *(C)* GSL 160.

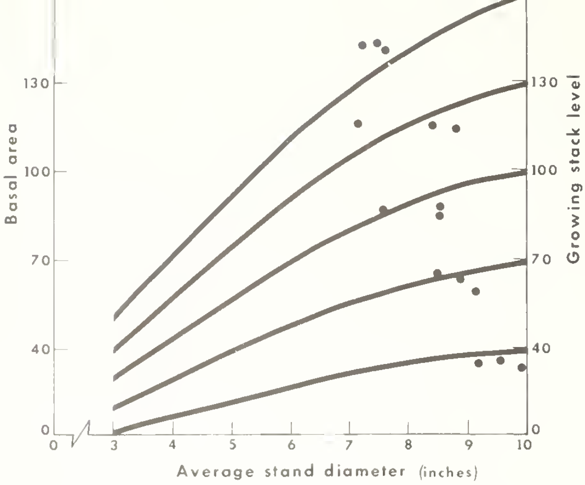


Figure 2—Basal area after thinning in relation to average stand diameter. The growing stock levels for ponderosa pine are standard (Myers 1967).

growth rate for the 5 years preceding thinning.

Stem volumes inside bark in cubic feet and board feet, Scribner, were calculated by Grosenbaugh's (1974) STX computer program as modified by Space (1974). Plot volumes immediately after thinning and five growing seasons later were obtained by the following equations.[1]

$$V = \frac{K}{n} \sum_{i=1}^{n} \frac{V_i}{est_i}$$

Five years later:

$$V = \frac{K}{n_5} \sum_{i=1}^{n_5} \frac{V_{i5}}{est_i}$$

in which
V = plot volume in cubic feet
K = total estimated plot volume in cubic feet immediately after thinning
n = number of dendrometered trees immediately after thinning
n_5 = number of dendrometered trees living 5 years later
V_i = volume measured by dendrometer of $tree_i$
est_i = estimated cubic volume of $tree_i$
V_{i5} = volume measured by dendrometer of living $tree_i$ 5 years later.

Stand characteristics immediately after thinning and 5 years later are presented on an acre basis in *table 2.*

GROWTH RELATED TO STOCKING LEVEL

Diameter

Periodic annual growth in diameter was influenced strongly by growing stock level. Trees in plots heavily thinned to GSL 40 grew most rapidly at the annual rate of 0.51 inch (1.3 cm) *(table 3).* At first, annual diameter growth declined rapidly with increasing stand density, then decreased to a rate of 0.21 inch (0.5 cm) annually for trees in plots lightly thinned to GSL 160 *(fig. 4).* Trees at GSL 40 and GSL 70 grew in diameter at rates significantly ($P \leqslant 0.05$) different from each other and all other stand densities. At higher stand densities, only trees at nonadjacent GSL's differed significantly because growth rate changes were small.

The largest trees in each plot also were influenced by stand density, but to a lesser extent than the average tree *(table 3).* Diameter growth rate of the 50 largest trees per acre (124 largest trees per ha) declined 37 percent compared to 59 percent for all trees when stand density increased from GSL 40 to GSL 160.

How does annual diameter growth of the leave trees after thinning compare with that before thinning? Nearly all trees were declining in growth rate at the time of thinning and, surprisingly, most growing stock levels did not halt that decline *(fig. 5).* Overall, the average leave tree grew 0.41 inch (1.0 cm) annually for the 5-year period before thinning. In the first year after thinning, only trees in plots heavily thinned to GSL 40 and GSL 70 grew more than before. Trees at higher stand densities grew at the same, or slower, rate than during the 5-years before thinning. Diameter growth rates for the second and third years continued to rise only in trees most heavily thinned (GSL 40). Trees at GSL 70 slowed in diameter growth to their pre-thinning rate. Trees at higher stand densities continued to decline.

---

[1] Personal communication, Nancy X. Norick and David A. Sharpnack, Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif., January 28, 1970.

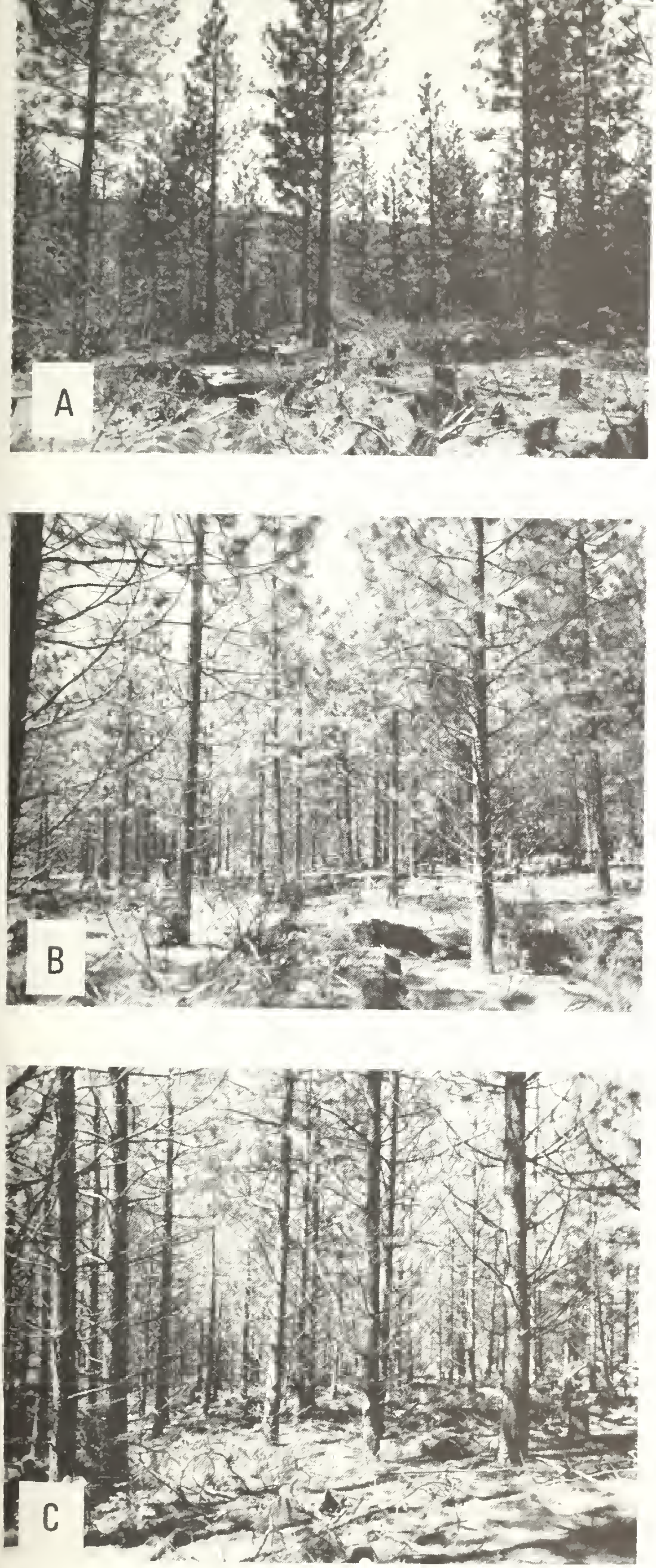


Figure 3— Five years after thinning the Elliot Ranch Plantation to growing stock levels of 40 *(A)*, 100 *(B)*, and 160 *(C)*.

that for the year before. The reason for this drastic drop in diameter growth is unclear. However, spring 1973 was unusually dry in the Sierra Nevada. After March 1, one-third less than normal rain fell, only about 1 inch (2.5 cm) of which fell after the start of the growing season. Noticeably reduced growth from drought seems unlikely, however, because total winter rainfall was sufficient to recharge the soil, and because the water-holding capacity of this soil is large.

More likely, reduced growth was caused by the severe cold that gripped northern California for 5 days in December 1972. Minimum temperatures at Elliot Ranch, as estimated from neighboring

fected when examined the following summer, thus ruling out winter desiccation—a common result of the cold wave seen elsewhere. Whatever the cause, diameter growth of ponderosa pine in 1973 was reduced in many areas on the westside of the Sierra Nevada.

Trees at all growing stock levels recovered in the fifth year to grow at a rate only slightly less than that of the third year. Over the 5-year period, only trees on plots heavily thinned to GSL 40 grew faster after thinning than before. Trees at GSL 70 grew about as fast as before thinning, and trees at all higher stand densities grew substantially less in rate of diameter growth after thinning.

Table 2—*Stand characteristics per acre after thinning a 20-year-old ponderosa pine plantation on a productive site to five growing stock levels and 5 years later*

Growing stock levels[1]	Plot no.	Total trees	D.b.h.	Height	Crown dimensions: Length	Crown dimensions: Width	Crown dimensions: Live crown	Basal area	Net Volume: Total[2]	Net Volume: Merch.[3]	Mortality
			Inches	*—— Feet ——*			*Percent*	*Sq. ft.*	*Cu. ft.*	*Bd. ft.*	*Cu. ft.*
					After thinning						
40	13	68	10.0	45	31	12	69	37	635	1620	
	10	84	9.1	40	27	12	66	38	624	789	
	8	80	9.5	40	29	12	72	39	579	1082	
70	15	144	9.0	44	31	12	70	63	1108	1673	
	7	156	8.7	37	26	11	71	64	1037	1435	
	5	174	8.3	35	26	11	74	65	960	0	
100	14	227	8.6	39	28	11	71	92	1568	1437	
	6	212	8.6	40	28	11	72	86	1226	1567	
	1	287	7.5	30	22	10	74	89	1277	576	
130	11	277	8.8	45	30	12	67	116	1907	909	
	4	322	8.2	37	26	11	71	118	1832	485	
	2	439	7.0	31	22	10	71	118	1871	408	
160	12	476	7.4	35	23	10	68	143	2195	1652	
	9	548	7.0	28	19	9	68	144	1886	1360	
	3	493	7.3	35	24	10	70	145	2033	1833	
					5 Years later						
40	13	68	12.6	58	36	17	62	59	1139	3403	0
	10	80	11.6	54	35	16	66	62	1245	3188	17
	8	78	12.1	50	34	18	69	64	1194	3144	5
70	15	142	10.8	54	36	17	67	92	1899	4429	7
	7	154	10.8	49	31	15	63	98	1863	4314	12
	5	172	10.1	43	28	15	66	96	1771	2389	5
100	14	219	10.2	50	31	15	63	128	2469	4856	48
	6	202	10.1	48	30	14	63	118	1957	3520	51
	1	283	8.8	37	24	13	66	122	2156	1667	17
130	11	269	10.2	56	34	16	60	159	3037	4684	36
	4	320	9.4	44	26	14	59	156	2704	2654	7
	2	425	8.1	38	21	12	57	157	2892	4049	31
160	12	458	8.6	44	24	13	56	193	3279	5663	71
	9	532	7.9	37	20	11	56	189	3276	3595	30
	3	485	8.3	43	25	12	58	185	3390	3019	24

[1] Stand density expressed as the basal area per acre that will remain after thinning when average stand diameter is 10 inches or more.
[2] Gross volume inside bark from ground line to tip less mortality.
[3] Scribner board feet to a 6-inch top inside bark and an 8-foot minimum log length, i.e., most trees 9 inches d.b.h.o.b. and larger.

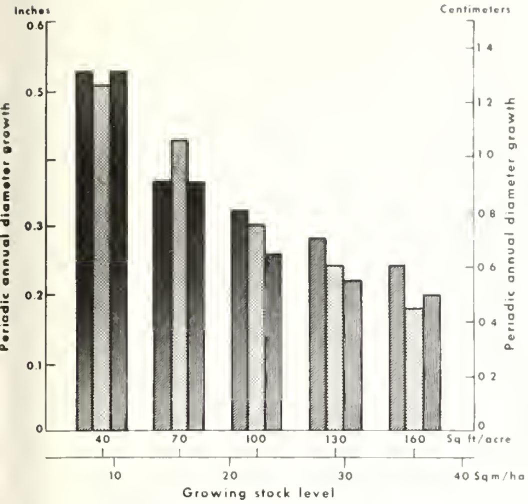


Figure 4— Diameter growth slowed with increasing levels of growing stock for 5 years after thinning a plantation of ponderosa pine poles on a productive site.

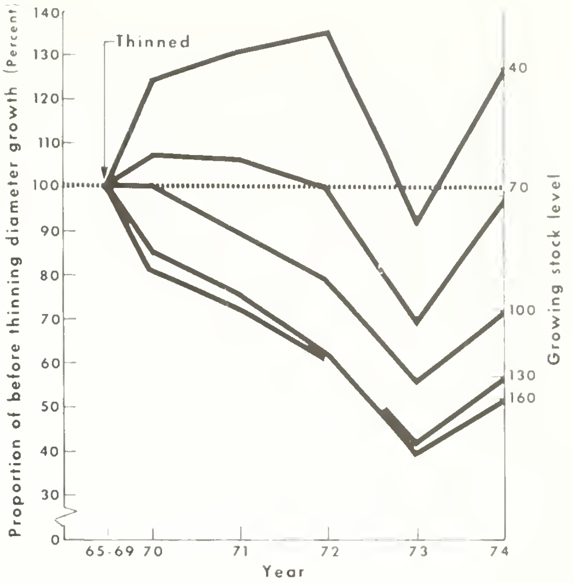


Figure 5— Only heavy thinning to growing stock level 70 or below increased diameter growth of leave trees in a plantation of ponderosa pine poles on a productive site.

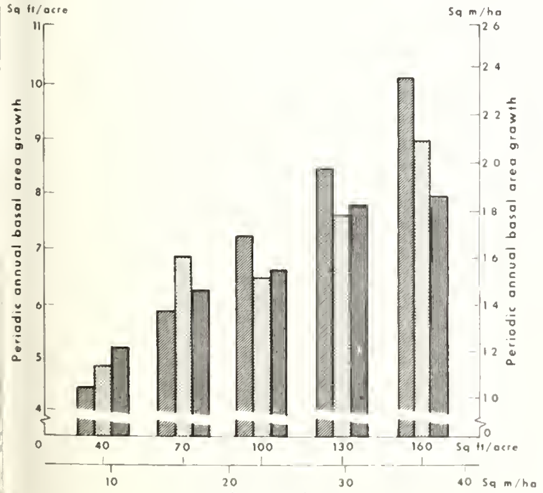


Figure 6— A plantation of ponderosa pine poles on a productive site grew more rapidly in basal area after thinning to higher levels of growing stock than it did to lower levels.

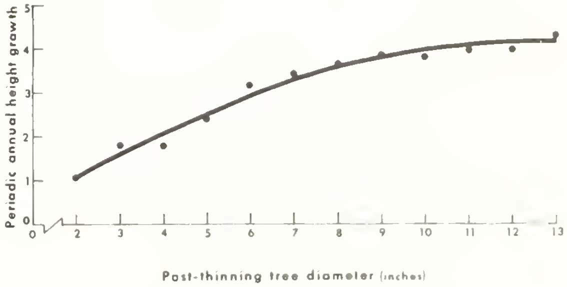


Figure 7— Height growth was related to tree size rather than growing stock level for the first 5 years after thinning a plantation of ponderosa pine on a productive site.

Basal Area

Periodic annual basal area growth was significantly and positively correlated with stand density for the 5 years since thinning *(table 3, fig. 6)*. Trees growing at GSL 40 grew 4.7 square feet per acre (1.1 m^2/ha) annually. Basal area growth increased with increasing stand density to 9.0 square feet per acre (2.1 m^2/ha) annually for GSL 160. Differences in basal area growth among stand densities were significant except between GSL 70 and GSL 100.

Height

Height growth was related strongly to tree diameter, rather than growing stock level, during the 5 years following thinning. In young, even-aged stands, larger trees usually grow faster in height than smaller trees. At Elliot Ranch, 98 percent of the variation among trees in 5-year height growth was related to post-thinning tree diameter *(fig. 7)*. No differences in this relationship among growing stock levels could be detected. The average tree in plots at higher growing stock levels did tend to grow less in height than the average tree at lower growing stock levels *(table 3)*. But this nonsignificant trend was caused by greater numbers of slower growing small trees present at the higher growing stock levels.

Crowns

Tree crowns were wide and long when the Elliot Ranch Plantation was thinned. Overall, the average tree after thinning had a crown 26 feet (7.9 m) long representing a live crown ratio of 70 percent, and 11 feet (3.4 m) wide *(table 2)*.

Since thinning, crowns widened at all stand der sities, but more so at the lower growing stock level The crown expanded 1 foot (0.3 m) annually fc trees in GSL 40 plots, decreasing linearly to 0.4 foc (0.1 m) for trees in GSL 160 plots. Difference among GSL's 40, 100, and 160 were significar *(table 3)*.

The live crown ratio, in contrast to crown widtl decreased at all stand densities; but this decreas was more pronounced at higher stand densitie After 5 years, live crown ratios were reduced fror the original 70 percent to 66 percent at GSL 40 an to 57 percent at GSL 160. However, the difference in rates of crown reduction among stand densitie were not strong. Only the lowest (GSL 40) and th two highest stand densities (GSL's 130 and 160) di fered significantly.

Volume

Stem volume production was impressive in th fully crowned trees which grew rapidly in botl diameter and height. Growth in total stem volum per acre was related strongly to growing stock leve during the 5 years after thinning *(fig. 8)*. Periodi annual volume growth rose at the rate of 1.3 cubi feet (0.04 m) for every square foot increase in stan basal area throughout the range of growing stoc levels tested. At GSL 40, trees grew 116 cubic fee per acre (8.1 m^3/ha) annually, rising to 255 cubi feet (17.8 m^3/ha) at GSL 160 *(table 3)*. Difference in volume growth were large and significant amon the lowest and highest stand densities (GSL 40 an GSL 160) and their adjacent treatment levels whereas differences were smaller and nonsignifi cant among the intermediate stand densities (GSL' 70, 100, and 130) and their adjacent treatmen levels.

Table 3—*Mean periodic annual growth for 5 years after thinning a plantation of ponderosa pine poles on a productive site to five growing stock levels*

Growing stock level[1]	D.b.h.	Height	Crown		Basal area	Net volume			Largest 50 trees/acre	
			Width	Ratio		Total[2]	Interest rate[3]	Merch.[4]	D.b.h.	Total volume
	Inch	*Feet*		*Percent*	*Sq. ft./ac*	*Cu. ft./ac*	*Percent*	*Bd. ft./ac*	*Inch*	*Cu. ft.*
40	[5]0.51	2.5	1.0	– 0.7	4.7	116	14	416	0.54	73
70	0.38	2.0	0.9	– 1.3	6.3	162	12	535	0.46	74
100	0.29	1.7	0.7	– 1.7	6.7	167	10	431	0.41	73
130	0.25	1.7	0.6	– 2.2	8.0	201	9	639	0.40	73
160	0.21	1.7	0.5	– 2.4	9.0	255	10	495	0.34	72

[1] Stand density expressed as the basal area per acre that will remain after thinning when average stand diameter is 10 inches or more.

[2] Gross volume inside bark from ground line to tip less mortality.

[3] Compounded annually on net volume.

[4] Scribner board feet to a 6-inch top inside bark and an 8-foot minimum log length, i.e., most trees 9 inches d.b.h.o.b. and larger.

[5] Means significantly different at 5 percent level are unbracketed.

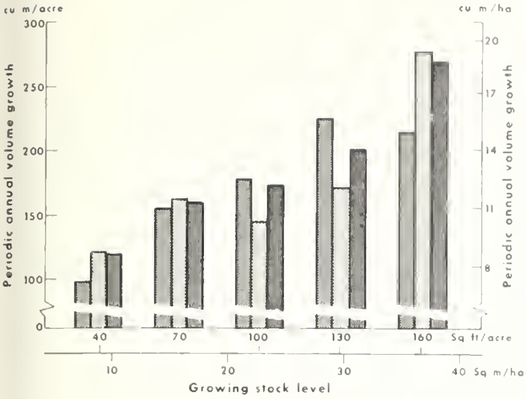


Figure 8—Volume growth was greater at higher growing stock levels for 5 years after thinning a plantation of ponderosa pine poles on a productive site.

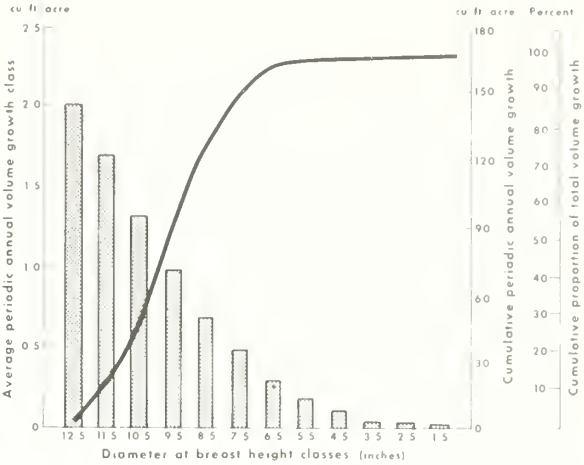


Figure 9—Annual volume growth and the cumulative volumes and proportions contributed by trees in various d.b.h. classes for 5 years after thinning a plantation of ponderosa pine poles on a productive site to growing stock level 100.

Volume growth percent also has been impressive, especially at the lower stand densities. Plots thinned to GSL 40 grew 116 cubic feet per acre (8.1 m^3/ha) annually on growing stock of only 613 cubic feet (42.9 m^3/ha) for a compound interest rate of 14 percent. Growth percent decreased slightly and leveled off at 10 percent for plots at GSL's 100 through 160.

Trees growing in stands of lower densities are individually more efficient volume producers because they are mostly large, rapidly growing, and dominant. For instance, in GSL 100 plots, trees 11.5 inches (29 cm) d.b.h. grew 1.8 cubic feet (0.05 m^3) annually; while trees 5.5 inches (14 cm) d.b.h. grew only 0.2 cubic feet (0.006 m^3) annually *(fig. 9)*. As a result, 77 percent of the volume production in plots thinned to GSL 100 was contributed by trees 8.5 inches d.b.h. (22 cm) and larger—trees larger than the average found on these plots.

The steady rise in stem volume production with increasing growing stock levels up to GSL 160 (144 ft^2/ac of basal area or 33.1 m^2/ha) sharply contrasts to the leveling off in volume production at GSL's between 80 (Schubert 1971, Oliver 1972) and 110 (Oliver 1979) found for pole-sized stands on less productive sites. Since site index at Elliot Ranch is about twice that of these less productive sites (50 to 60 against 115), I expect a concomitant rise in stand density at which maximum volume is produced. At Elliot Ranch, maximum production was not reached at GSL's below 160.

Merchantable volume growth has little meaning for tree sizes similar to those at Elliot Ranch. Small differences in diameter distributions among plots create large differences in board-foot production, obscuring the effect of growing stock level. Rapid accumulation of board feet was fueled largely by ingrowth into merchantable sizes. The smallest tree considered merchantable was 9 inches (23 cm) d.b.h. capable of producing an 8-foot (2.4-m) log with a 6-inch (15-cm) diameter inside bark at the small end—intensive utilization by today's standard. The proportion of trees reaching this merchantable size averaged 31 percent for all plots during the 5 years since thinning. The proportion tended to be greater at lower growing stock levels.

DAMAGE AND MORTALITY

Tree injury and death have had little influence on 5-year results *(table 2)*. A heavy, wet snowfall in winter 1970 caused nearly all damage and mortality. Stems broke at or below the crown base, killing 39 trees or 1.9 percent of all trees in the study. Also included as dead were a few living trees cut during a clean-up in the spring following the storm. Since most of the crown had broken out of these trees, I expected them to die soon. If not removed, they might have bred bark beetles.

Snow broke the upper crowns or bent the stems of 9.4 percent of all study trees. Damage from an earlier storm at the Elliot Ranch Plantation was greater in stands of higher densities than in stands of lower densities (Powers and Oliver 1970). I found a similar but nonsignificant trend in both damage and mortality after the 1970 storm.

CONCLUSIONS

A periodic annual volume growth of 255 cubic feet per acre (17.8 m^3/ha) reported in this study for plots growing at GSL 160 may seem unusually high. However, this growth rate is about that predicted by Meyer (1938) and Oliver and Powers (1978). It compared favorably with rates reported for similar plantations of loblolly and slash pine in the southern United States (Feduccia and Mann 1976, Mann and Enghardt 1972).

Plantations often grow faster than comparable natural stands, especially at young ages, because competition among trees and with other vegetation is reduced. At Elliot Ranch, deerbrush was plentiful but scarcely retarded growth and development of the plantation because moisture and nutrients were abundant. Stocking control, through planting which resulted in less intertree competition, influenced thinning response profoundly. Before thinning, the uniformly spaced leave trees were healthy and vigorous, as indicated by an average live crown ratio of 70 percent. Periodic annual growth in both diameter and volume was at its peak (Meyer 1938, Oliver and Powers 1978). After thinning, when the stand was 20 years old, leave trees responded immediately to the added space made available. But only trees in plots thinned to the two lightest growing stock levels—GSL 40 and GSL 70—grew faster in diameter after thinning than before. And the increased growth of trees in GSL 70 plots was fleeting, lasting only 2 years. Diameter growth of trees at all higher growing stock levels continued their normal decline following culmination of periodic annual growth. Live crown ratio was not stimulated by thinning even to GSL 40, because leave tree crowns were full before thinning. Instead, thinning slowed the decline in live crown ratio which is normal with advancing age regardless of stand density.

Board-foot volume growth remained nearly constant and total volume growth increased linearly with increasing growing stock levels throughout the range of levels tested. Although not tested, unthinned plots probably would have grown in total stem volume at a rate even faster than GSL 160 plots. If so, thinning in plantations not under sever intertree competition may be at the sacrifice c potential volume production. But the growth los has no practical importance because thinnings fro pole-sized plantations have little commercial valu in today's market.

Since thinning may reduce per acre growth (eve though the volume lost is presently without commercial value), what advantages are gained by thinning these "high site" ponderosa pine plantations Shortening the time to reach merchantable size is major advantage. Growth of GSL 160 plots ma seem adequate, but thinning to GSL 100 will brin the plantation to merchantable size 15 years soone —at age 35 years for GSL 100 against age 50 fo GSL 160, assuming that the plantation would b thinned once when pole-sized and that a mea stand diameter of 12 inches soon will be minimu merchantable size (yielding trees 9 to 12 inches in a low thinning).

Another advantage of thinning is stand health. Densities in unthinned plantations approaching 300 square feet of basal area per acre at age 50 are likely. Growth losses, including mortality, from intertree competition and possibly bark beetles (Sartwell and Stevens 1975) could be substantial. By contrast, stands thinned to GSL 100 could reach 200 square feet of basal area per acre at age 35 years. This density is sufficient to support a commercial thinning, but probably not dense enough to jeopardize stand health on this productive site.

Precommercial thinning pole-sized plantations is not recommended. Thinning is costly. Also, the huge volume of slash creates an unacceptable fire and insect hazard. The cost to mitigate this hazard often is prohibitive. Thinning when trees have reached sapling size usually reduces thinning costs and slash volumes to acceptable levels.

These conclusions are based upon stand density-growth relationships found in only one plantation. Although they seem reasonable, the conclusions may not apply to other plantations.

LITERATURE CITED

Feduccia, D. P. and W. F. Mann, Jr.
1976. **Growth following initial thinning of loblolly pine planted on a cutover site at five spacings.** U.S. Dep. Agric. Forest Serv. Res. Paper SO-120, 8 p., illus. Southern Forest Exp. Stn., New Orleans, La.

Grosenbaugh, L. R.
1974. **STX 3-3-73: Tree content and value estimation using various sample designs, dendrometry methods, and V-S-L conversion coefficients.** USDA Forest Serv. Res. Paper SE-117, 112 p., illus. Southeastern Forest Exp. Stn., Asheville, N.C.

Mann, W. F., Jr., and Hans G. Enghardt.
1972. **Growth of planted slash pine under several thinning regimes.** U.S. Dep. Agric. Forest Serv. Res. Paper SO-76, 10 p. Southern Forest Exp. Stn., New Orleans, La.

Meyer, Walter H.

1938. **Yield of even-aged stands of ponderosa pine.** U.S. Dep. Agric. Tech. Bull. 630, 59 p., illus.

Myers, Clifford A.

1967. **Growing stock levels in even-aged ponderosa pine.** U.S. Forest Serv. Res. Paper RM-33, 8 p., illus. Rocky Mtn. Forest and Range Exp. Stn., Fort Collins, Colo.

Oliver, William W.

1972. **Growth after thinning ponderosa pine and Jeffrey pine pole stands in northeastern California.** USDA Forest Serv. Res. Paper PSW-85, 8 p., illus. Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif.

Oliver, William W.

1979. **Fifteen-year growth patterns after thinning a ponderosa-Jeffrey pine plantation in northeastern California.** Res. Paper PSW-141, 10 p., illus. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

Oliver, William W., and Robert F. Powers.

1978. **Growth models for ponderosa pine: I. Yield of unthinned plantations in northern California.** Res. Paper PSW-133, 21 p., illus. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

Powers, Robert F., and William W. Oliver.

1970. **Snow breakage in a pole-size ponderosa pine plantation... more damage at high stand densities.** USDA Forest Serv. Res. Note PSW-218, 3 p., illus. Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif.

Powers, Robert F., and William W. Oliver.

1978. **Site classification of ponderosa pine stands under stocking control in California.** USDA Forest Serv. Res. Paper PSW-128, 9 p., illus. Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif.

Sartwell, Charles, and Robert E. Stevens.

1975. **Mountain pine beetle in ponderosa pine—prospects for silvicultural control in second-growth stands.** J. For. 73(3): 136-140, illus.

Schubert, Gilbert H.

1971. **Growth response of even-aged ponderosa pines related to stand density levels.** J. For. 69(12):857-860, illus.

Sindel, Glen E.

1963. **The use of cattle to control deerbrush growth during pine plantation establishment.** Soc. Am. For. Proc. 1962:71-72.

Space, James C.

1974. **3-P forest inventory: design procedures, data processing.** U.S. Forest Serv. State and Private For., Southeastern Area, Atlanta, Ga. 58 p., illus.

U.S. Department of Agriculture, Soil Conservation Service.

1975. **Soil taxonomy.** U.S. Dep. Agric., Agric. Handb. 436, 754 p., illus.

The Forest Service of the U.S. Department of Agriculture

- . . . Conducts forest and range research at more than 75 locations from Puerto Rico to Alaska and Hawaii.
- . . . Participates with all State forestry agencies in cooperative programs to protect and improve the Nation's 395 million acres of State, local, and private forest lands.
- . . . Manages and protects the 187-million-acre National Forest System for sustained yield of its many products and services.

The Pacific Southwest Forest and Range Experiment Station
represents the research branch of the Forest Service in California and Hawaii.

1979. **Growth of planted ponderosa pine thinned to different stocking**

Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

Growth was strongly related to growing stock level (GSL) for 5 years after thinning 20-year-old poles on Site Index$_{50}$ 115 land at the Elliot Ranch Plantation in northern California. Five GSL's—basal areas anticipated when trees average 10 inches d.b.h. or more—ranging from 40 to 160 square feet per acre were tested. Periodic annual increment (PAI) in diameter decreased curvilinearly from 0.51 to 0.21 inch, with increasing GSL's from 40 to 160. But only trees in plots heavily thinned to GSL 40 (and briefly in GSL 70) grew faster in diameter after thinning than these same trees grew before thinning. PAI in basal area and net volume rose steadily with increasing GSL's, reaching 9.0 square feet and 255 cubic feet per acre, respectively, at GSL 160. Apparently, even light thinning reduced volume production, but thinning still is recommended to shorten time until first commercial entry and to promote stand health.

Retrieval Terms: Pinus ponderosa, stand density-growth, diameter growth, basal area growth, volume growth, stocking level, plantation, California.

1979. **Growth of planted ponderosa**

Res. Paper PSW-147, 11 p., illus. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

Growth was strongly related to growing stock level (GSL) for 5 years after thinning 20-year-old poles on Site Index$_{50}$ 115 land at the Elliot Ranch Plantation in northern California. Five GSL's—basal areas anticipated when trees average 10 inches d.b.h. or more—ranging from 40 to 160 square feet per acre were tested. Periodic annual increment (PAI) in diameter decreased curvilinearly from 0.51 to 0.21 inch, with increasing GSL's from 40 to 160. But only trees in plots heavily thinned to GSL 40 (and briefly in GSL 70) grew faster in diameter after thinning than these same trees grew before thinning. PAI in basal area and net volume rose steadily with increasing GSL's, reaching 9.0 square feet and 255 cubic feet per acre, respectively, at GSL 160. Apparently, even light thinning reduced volume production, but thinning still is recommended to shorten time until first commercial entry and to promote stand health.

Retrieval Terms: Pinus ponderosa, stand density-growth, diameter growth, basal area growth, volume growth, stocking level, plantation, California.

Oliver, William W.
1979. **Growth of planted ponderosa pine thinned to different stocking levels in northern California**. Res. Paper PSW-147, 11 p., illus. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

Growth was strongly related to growing stock level (GSL) for 5 years after thinning 20-year-old poles on Site Index$_{50}$ 115 land at the Elliot Ranch Plantation in northern California. Five GSL's—basal areas anticipated when trees average 10 inches d.b.h. or more—ranging from 40 to 160 square feet per acre were tested. Periodic annual increment (PAI) in diameter decreased curvilinearly from 0.51 to 0.21 inch, with increasing GSL's from 40 to 160. But only trees in plots heavily thinned to GSL 40 (and briefly in GSL 70) grew faster in diameter after thinning than these same trees grew before thinning. PAI in basal area and net volume rose steadily with increasing GSL's, reaching 9.0 square feet and 255 cubic feet per acre, respectively, at GSL 160. Apparently, even light thinning reduced volume production, but thinning still is recommended to shorten time until first commercial entry and to promote stand health.

Retrieval Terms: Pinus ponderosa, stand density-growth, diameter growth, basal area growth, volume growth, stocking level, plantation, California.

Oliver, William W.
1979. **Growth of planted ponderosa pine thinned to different stocking levels in northern California**. Res. Paper PSW-147, 11 p., illus. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

Growth was strongly related to growing stock level (GSL) for 5 years after thinning 20-year-old poles on Site Index$_{50}$ 115 land at the Elliot Ranch Plantation in northern California. Five GSL's—basal areas anticipated when trees average 10 inches d.b.h. or more—ranging from 40 to 160 square feet per acre were tested. Periodic annual increment (PAI) in diameter decreased curvilinearly from 0.51 to 0.21 inch, with increasing GSL's from 40 to 160. But only trees in plots heavily thinned to GSL 40 (and briefly in GSL 70) grew faster in diameter after thinning than these same trees grew before thinning. PAI in basal area and net volume rose steadily with increasing GSL's, reaching 9.0 square feet and 255 cubic feet per acre, respectively, at GSL 160. Apparently, even light thinning reduced volume production, but thinning still is recommended to shorten time until first commercial entry and to promote stand health.

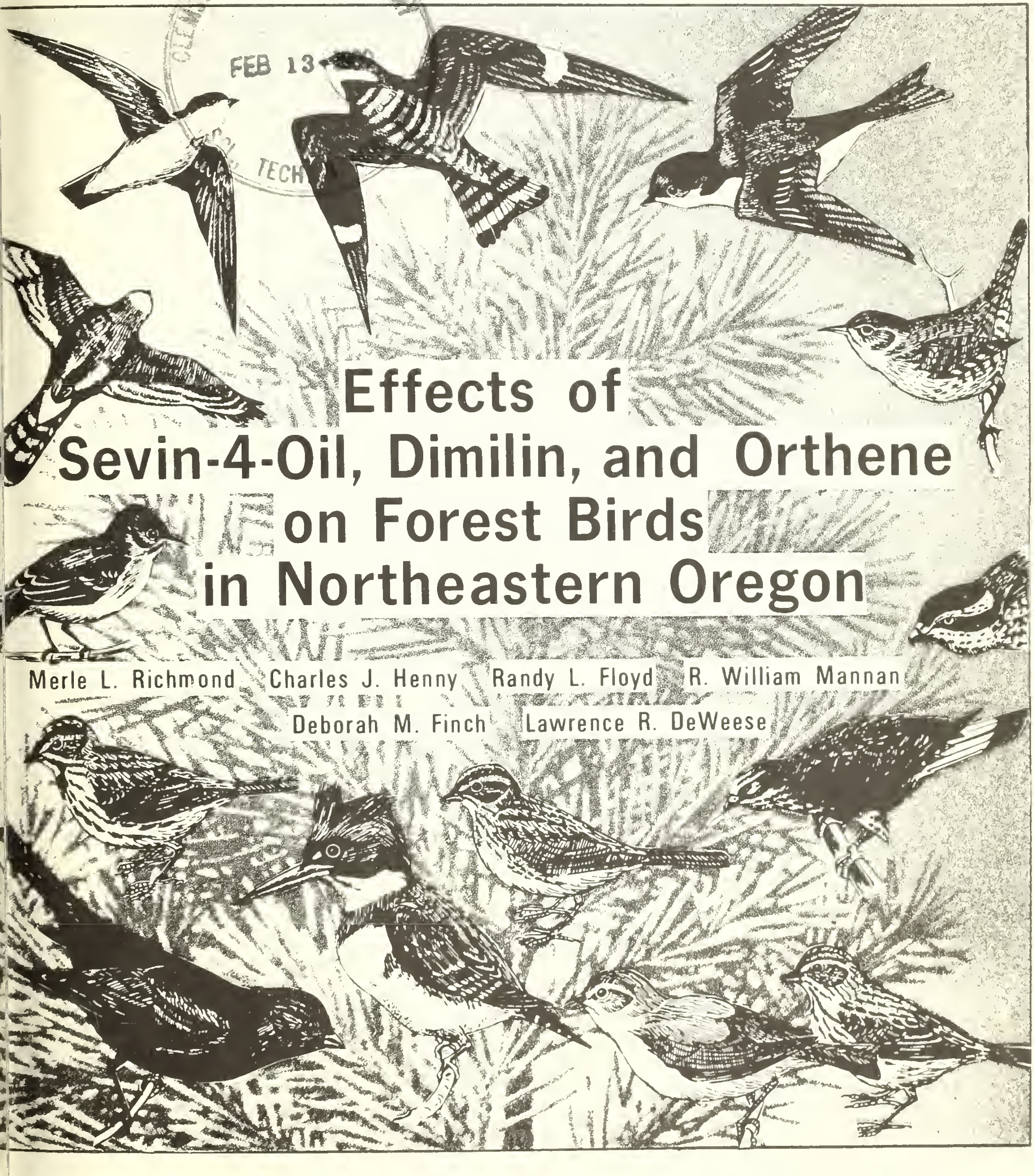
Retrieval Terms: Pinus ponderosa, stand density-growth, diameter growth, basal area growth, volume growth, stocking level, plantation, California.

OVT. DOCUMENTS
EPOSITORY ITEM
FEB 11 1980
CLEMSON
LIBRARY

REST SERVICE
.DEPARTMENT OF AGRICULTURE

PACIFIC SOUTHWEST
Forest and Range
Experiment Station

CLEMSON UNIVERSITY LIBRARY
FEB 13
TECH



Effects of Sevin-4-Oil, Dimilin, and Orthene on Forest Birds in Northeastern Oregon

Merle L. Richmond Charles J. Henny Randy L. Floyd R. William Mannan
Deborah M. Finch Lawrence R. DeWeese

RESEARCH PAPER PSW-148

The Authors

MERLE L. RICHMOND is a wildlife biologist, Fish and Wildlife Service, U.S. Department of Interior, stationed at Portland, Oregon. He received a bachelor of science degree from Colorado State University in 1962. **CHARLES J. HENNY** is leader, Pacific Northwest Field Station, Patuxent Wildlife Research Center, Fish and Wildlife Service, U.S. Department of Interior, Corvallis, Oregon. He earned a master of science degree (1967) in wildlife management, and a doctorate (1970) in wildlife ecology from Oregon State University. **RANDY L. FLOYD, R. WILLIAM MANNAN**, and **DEBORAH M. FINCH** were members of the staff of the Fish and Wildlife Service during the study. **FLOYD** holds a bachelor of science degree (1975) in wildlife science from Oregon State University. **MANNAN** holds a bachelor of arts degree (1974) in biology from Hanover College, Indiana, and a master of science degree (1977) in wildlife ecology from Oregon State University. **FINCH** holds a bachelor of science degree (1978) in wildlife ecology from Humboldt State University. **LAWRENCE R. DeWEESE** is a wildlife biologist, research, Fish and Wildlife Service, stationed at Fort Collins, Colorado. He received a bachelor of science degree in wildlife biology from Colorado State University in 1968.

ACKNOWLEDGMENTS

We are grateful for the participation of many persons in the study reported here. From the Fish and Wildlife Service, U.S. Department of Interior, Barbara Sprang, Siri Jackman, and Patricia Domanski assisted in establishment of study plots and initial bird counts, and Kathie Bobal and Albert Schultz collected field data during the 1976 field season. Joseph Zinkl (University of California, Davis) analyzed the birds for cholinesterase activity. Patrick Shea (Pacific Southwest Forest and Range Experiment Station) skillfully coordinated the aerial applications of insecticides and other activities throughout the field study. Jack W. Thomas (Pacific Northwest Forest and Range Experiment Station) kindly allowed use of the Range and Wildlife Habitat Laboratory facilities at La Grande; members of his staff assisted us throughout the study. The manuscript benefited from the comments of Kenneth L. Stromborg and Stana Federighi (Fish and Wildlife Service), George Ferrell (Pacific Southwest Station), Robert Campbell (Pacific Northwest Station), and Donald Dahlsten (University of California, Berkeley). The work leading to this publication was funded in part by a program sponsored by the U.S. Department of Agriculture, the Expanded Douglas-fir Tussock Moth Research and Development Program.

usda douglas-fir tussock moth • research & development program •

Effects of Sevin-4-Oil, Dimilin, and Orthene on Forest Birds in Northeastern Oregon

Merle L. Richmond   Charles J. Henny   Randy L. Floyd   R. William Mannan
Deborah M. Finch   Lawrence R. DeWeese

CONTENTS

Introduction 1
Study Area 2
Methods 3
  Insecticide Treatments 3
  Census Techniques 3
  Nesting Success Estimates 4
  Brain Cholinesterase Studies 5
  Plot Comparability Tests 5
Results and Discussion 5
  Population Composition 6
  Nesting Success 7
  Brain Cholinesterase 8
Conclusions 9
Recommendations 11
  Field Tests 11
  Pilot Control Study 12
Literature Cited 12
Appendix 15
  Species Check List 15

Pacific Southwest Forest and Range Experiment Station
P.O. Box 245
Berkeley, California 94701

September 1979

IN BRIEF...

Richmond, Merle L., Charles J. Henny, Randy L. Floyd, R. William Mannan, Deborah M. Finch, and Lawrence R. DeWeese.
1979. **Effects of Sevin-4-Oil, Dimilin, and Orthene on forest birds in Northeastern Oregon.** Res. Paper PSW-148, 19 p., illus. Pacific Southwest Forest and Range Exp. Stn., Forest Service, U.S. Dep. Agric., Berkeley, Calif.

Retrieval Terms: Sevin-4-Oil (carbaryl); Orthene (acephate); Dimilin (diflubenzuron); forest birds; brain cholinesterase.

A field study begun in 1975 in the forests of northeastern Oregon was designed to assess the effects of Dimilin (at 0.14 and 0.28 kg/ha), Sevin-4-Oil (at 2.24 kg/ha), and Orthene (at 1.12 and 2.24 kg/ha) on a nontarget nesting bird population. Eleven study plots (six treatment and five control plots) were established in the Wallowa-Whitman National Forest. Breeding bird density, species diversity, nesting success, brain cholinesterase (ChE) activity, and the presence of sick or dead birds were evaluated on control and treatment plots during the study period in the year of spraying (1976) and 1 year after spraying.

Two bird census techniques were used (spot-mapping and fixed station index). Calculations of the probability of success of nest contents were based on nest-days of exposure to allow use of incomplete nest records. Because organophosphate and carbamate insecticides like Orthene and Sevin-4-Oil inhibit cholinesterase enzymes, we measured brain ChE activities of collected birds to determine the extent and magnitude of exposure to the insecticides.

We did not find any sick or dead birds, or observe any abnormal behavior in birds on plots treated with Dimilin or Sevin-4-Oil. Furthermore, cholinesterase tests of birds from plots treated with Sevin-4-Oil showed only 2 of 55 birds with brain ChE depression. However, several observations of abnormal activity in forest birds were made following the application of Orthene. In marked contrast to Sevin-4-Oil, Orthene caused extensive inhibition of brain ChE activity (commonly 30 to 50 percent) for up to at least 33 days for 11 of 12 species collected. The highest frequency of depression (12 out of 13 birds or 92 percent) was noted on the second day following spray. Postspray bird census data suggest that two species of birds may have decreased in numbers following the Orthene treatment. The overall impact of Orthene on the nesting bird population is not fully understood and further testing is necessary. One year postspray, 11 birds (6 species) were collected on the plot treated with Orthene at 1.12 kg/ha and the brain ChE activity from all samples was within the normal range.

The evaluation of bird populations was complicated by (1) movements of birds into and out of the small treated plots, (2) presence of floating surplus individuals, and (3) variability in numbers of birds detected, because bird behavior changed with weather conditions and at different stages of the nesting cycle. Furthermore, since replications of study plots were not feasible, no analysis of variance of the data could be made; consequently interpretation of the results was partly subjective. The absence of an insect outbreak on the study plots may have also influenced the results if the ingestion of sick or dying insects is a major route through which birds encounter pesticides. Some of the difficulties are inherent in most field studies of birds.

The findings from the study were compared with the available literature; other studies differ in evaluation procedures, size of plots, and the presence or absence of insect outbreaks at the time of the investigations. Restraints on funds and manpower require that priorities be established so as to use the most sensitive research methods in determining the insecticide effects on birds. We recommend these research methods should receive priority: (1) studies of brain ChE activity (specific for effects of organophosphate and carbamate insecticides), (2) nesting studies, (3) bird behavior observations, and (4) census of populations.

The possible harmful effect of insecticides on nontarget organisms should be a prominent concern in all attempts to control forest pests. Although all wildlife must be considered, birds are particularly vulnerable. The study reported here was part of the effort to find an environmentally safe method to control one of the major sources of insect damage to forest trees—the Douglas-fir tussock moth (*Orgyia pseudotsugata* [McDunnough]). Its larval stage is an important defoliator of true firs (*Abies* sp.) and Douglas-fir (*Pseudotsuga menziesii* var. *glauca* [Beissn.] Franco) in western North America. In Oregon, severe infestations have recurred at intervals of about 10 years since 1936 (Wickman and others 1973).

A tussock moth infestation lasting from 1971 to 1974 covered almost 325,000 ha of forest in northeastern Oregon, southeastern Washington, Idaho, and western Montana (Graham and others 1975). To combat the infestation, DDT, though banned by the U.S. Environmental Protection Agency (EPA) in 1972, was cleared for emergency use against the tussock moth in 1974. During June and July of that year, 172,600 ha of the forest were sprayed. Strong controversy over the use of DDT led to widespread support for finding alternative means of control.

As a result, the U.S. Department of Agriculture began a 4-year effort to find new answers to the problem. The USDA Expanded Douglas-fir Tussock Moth Research and Development Program, begun in October 1974, had two major goals: (1) to put into use methods presently available to reduce damage caused by tussock moth infestations, and (2) to develop new knowledge necessary to prevent or suppress future infestations (Wright 1977).

To meet these broad objectives, the planning group set up a five-phase program. Phase 3 dealt with new or improved materials and methods for suppression with emphasis on new chemical and biological control agents that were both effective and environmentally safe.

As part of this effort, a 3-year field study, begun in 1975 on the Wallowa-Whitman National Forest in northeastern Oregon, assessed the environmental effects of three insecticides—Sevin-4-Oil (carbaryl), Orthene (acephate), and Dimilin (diflubenzuron)—on nontarget organisms. Under contract, the U.S. Fish and Wildlife Service studied the effects of these insecticides on breeding birds.

A specific objective of the study was to determine, by measuring and comparing bird populations before and after treatments, whether the insecticide treatments resulted in the desertion of breeding territories, or in the sickness and death of breeding birds. We also hoped, by studying nesting activities on treated and untreated plots, to determine whether the insecticide treatments jeopardized the survival of eggs or nestlings. In addition, because organophosphate and carbamate insecticides like those being tested inhibit cholinesterase enzymes, we measured brain cholinesterase activities of collected birds to determine the extent and magnitude of exposure to the insecticide.

The methodology for studying the impact of the newer, less persistent insecticides on bird popula-

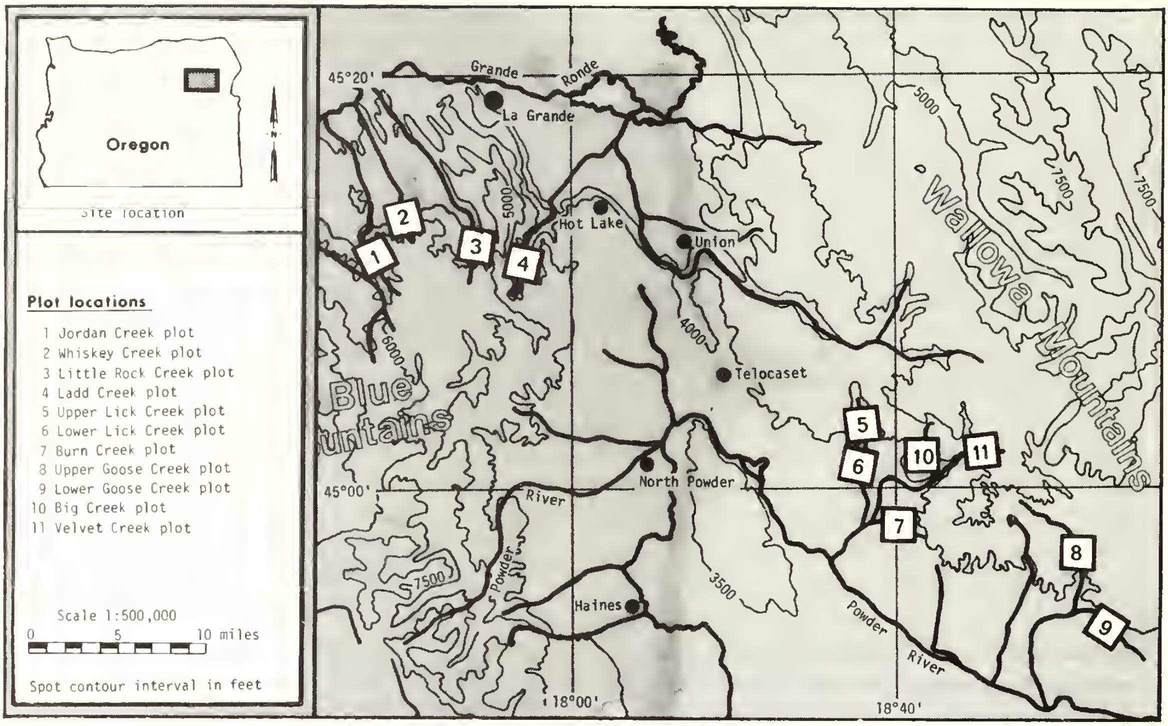


Figure 1—Study plots were established in the Wallowa Mountains and Blue Mountains of northeastern Oregon.

tions is in its early stages of development. Thus, no standard criteria for conducting field studies was available at the time this study was begun. Limitations of this particular study are discussed in detail in the conclusions section. Although some of our findings are partially based upon a subjective assessment, the details presented are important for their description of bird populations and for guidance in future studies. We believe the recommendations section will be useful as a guide for future investigations.

STUDY AREA

The study plots were established on the Union and La Grande Districts of the Wallowa-Whitman National Forest in northeastern Oregon *(fig. 1)*. Criteria used to select study plots were (1) presence of tussock moth habitat, (2) presence of permanent streams with riparian vegetation (to ensure an adequate diversity of bird species), (3) accessibility by road, (4) no proposed vegetation manipulation until after August 1977, and (5) no previous applications of DDT.

Elevations of the study plots ranged from 1183 m to 1677 m. Although all study plots were in the *Abies grandis* vegetation zone (Franklin and Dyrness 1973), there were noticeable differences between forests on the Union District (Wallowa Mountains) and those on the La Grande District (Blue Mountains).

Forests in the Wallowa Mountains were, in general, open, dry, and composed of a mosaic of plant associations dominated by one of the following: climax stands of grand fir (*Abies grandis* [Dougl.] Lindl.) mixed with western larch (*Larix occidentalis* Nutt.) and Douglas-fir; seral stands of ponderosa pine (*Pinus ponderosa* Dougl. ex Loud.) and Douglas-fir; open, rocky areas with scattered ponderosa pine; or deciduous stands of mountain alder (*Alnus incana* [L.] Moench), red-stemmed maple (*Acer glabrum* Torr.), and black cottonwood

(*Populus trichocarpa* Torr. & Gray). Associations dominated by deciduous trees occurred primarily along streams; those dominated by coniferous species were found upslope.

Forests on study plots in the Blue Mountains were generally more dense and mesic than on plots in the Wallowa Mountains, and consisted of seral stands of ponderosa pine, lodgepole pine (*Pinus contorta* Dougl. ex Loud.), and Douglas-fir, and climax stands of grand fir mixed with Engelmann spruce (*Picea engelmanii* Parry ex Engelm.), subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.), and western larch. Selective logging had occurred on all study plots.

During the data collection periods, June 6 to July 11, 1976, and May 27 to July 18, 1977, daily mean temperatures and ranges (°C) on study plots were as follows:

	1976	*1977*
Wallowa Mountains:		
Minimum	7.2	6.0
	(−3.3 to 19.4)	(1.7 to 12.8)
Maximum	22.8	27.8
	(10.1 to 33.3)	(7.3 to 32.8)
Blue Mountains:		
Minimum	4.1	6.2
	(−2.8 to 12.2)	(−2.8 to 13.3)
Maximum	27.8	21.9
	(7.8 to 28.9)	(7.3 to 31.1)

Total rainfall on plots in the Wallowa Mountains was 3.5 cm in 1976 and 0.7 cm in 1977. On plots in the Blue Mountains, the rainfall measurements were 4.5 cm in 1976 and 3.7 cm in 1977.

METHODS

During the summer of 1975 and spring of 1976, we established 11 study plots on the two districts. Each study plot of 129.5 ha consisted of an 80.9-ha square for bird population studies, which included an 8.09-ha subplot in the center, for more intensive research (breeding pair determination); and an adjoining 48.6-ha area for bird collection.

Where possible, for similarity, each treatment plot was assigned a control. Where two plots were established on one stream, the upstream plot was the control *(fig. 1)*.

Table 1—*Treatment allocation of study plots, Wallowa-Whitman National Forest*

Treatment plot and control	Treatment[1]	Rate	Application date (1976)
		kg/ha	
Wallowa Mountains:			
Lower Goose Creek (Upper Goose Creek)[2]	Sevin-4-Oil	2.24	June 27
Lower Lick Creek (Upper Lick Creek)[2]	Sevin-4-Oil	2.24	June 27
Big Creek (Burn Creek)[2]	Dimilin	0.14	June 26
Velvet Creek	Dimilin	0.28	June 26
Blue Mountains:			
Ladd Creek (Little Rock Creek)[2]	Orthene	1.12	June 23
Jordan Creek (Whiskey Creek)[2]	Orthene	2.24	June 24

[1] All applications were made in 1 gallon total formulation per acre. Solvent for Sevin-4-Oil was No. 2 fuel oil; for Dimilin and Orthene, H_2O + 10 percent ethylene glycol.

[2] Control plots.

Insecticide Treatments

During the last week of June 1976, the six treatment plots were sprayed with varying rates of Sevin-4-Oil, Dimilin, or Orthene[1] *(table 1)*. The treatments were applied with a conventional nozzle and boom system mounted on a Bell 206B Jet Ranger helicopter. Tee-Jet fan nozzle tips (no. 8002) were used to approximate a drop size of less than 250 microns VMD. All treatments were applied in 22.9 m swaths at 96 km/hr and at pressure of 2.8 kg/cm^2.

Census Techniques

To evaluate the effects of insecticides on breeding birds, we compared bird populations on treated plots with those on control plots. Two independent census techniques were used to assess bird abundance, the spot-mapping technique (Williams 1936, Hall 1964, Robbins 1970) and a fixed-station census. The census procedures used in this study are the same as used by DeWeese and others (1979). Their paper should be consulted for detailed methodology.

Numbers of breeding pairs were estimated on the 8.09-ha subplots by the spot-mapping technique.

---

[1] Trade names are mentioned solely for information. No endorsement by the U.S. Department of Agriculture is implied.

We conducted at least eight censuses (four before and four after spray) on each subplot between June 7 and July 11, 1976. In 1977, we conducted at least nine censuses on each subplot between May 27 and July 18. Each census was completed in 2 hours, beginning at sunrise. We excluded data for certain birds (calliope hummingbird, brown-headed cowbird, Cassin's finch, pine siskin, and red crossbill) from the estimates of breeding pairs because the territorial behavior of these species cannot be interpreted by the spot-mapping technique. (Note: See Appendix for scientific names of birds mentioned in this report.)

We recognized the weakness of relying on only the breeding-pair estimates for detecting population changes after treatment. Although population reductions can be detected by this technique, critics estimate that at best it uncovers only about one-fourth of an actual reduction (Robbins 1963). Also, repopulations after loss may occur so rapidly that the actual reduction may be masked by immigration of surplus breeders (Stewart and Aldrich 1951). So, since low magnitude population changes may not be detected by the breeding-pair mapping technique alone, we also employed the fixed station census.

The fixed-station census method provided an index of relative abundance — not the density estimate (number of pairs for a given area) obtained from the spot-mapping technique. Using a compass and surveying tape, we established 14 stations, spaced 161 m apart, between the boundaries of the 80.9-ha plot and the 8.09-ha subplot. A standardized route with stops at each of the 14 points was traversed in 2 hours. At each stop the observer rested for 1 minute and then recorded all birds heard or seen for a period of 5 minutes. Care was taken to avoid duplicating counts of an individual that moved from one place to another during the 5-minute period. Fixed-station censuses immediately followed spot-mapping censuses. Results of fixed-station censuses were expressed as the mean number of birds per point. The fixed-station census may be better for detecting short-term population changes immediately postspray.

The plots treated with Orthene were censused by the same observers in 1976 and 1977; however, on the plots treated with Dimilin and Sevin-4-Oil, different observers were used in 1976 and 1977. Therefore, between-year differences in bird populations on the Dimilin and Sevin-4-Oil plots may have been influenced by observer's ability, but any bias would be present also in the control plots, which were evaluated by the same observers as the treatment plots.

To reduce the variance in our analysis, we stratified bird species according to nest type and potential direct exposure to falling spray. Our categories were (1) open-nesters with high, medium, and low exposure to spray, and (2) cavity-nesters. Exposure categories were based on the parts of the habitat a species generally occupies when foraging and nesting (for example, birds of upper canopy, high direct exposure). These categories were also used when evaluating the fixed-station index and the estimates of breeding pairs.

To measure the degree of similarity in species composition between plots, we used data from fixed-station censuses to calculate similarity indexes. They were based on the "coefficient of community" (Bray and Curtis 1957), and express the degree to which two plots shared species. Moulding (1976) described the calculation of the index as it applied to bird populations.

We used data from fixed-station censuses to calculate diversity indexes for prespray and postspray populations. We calculated the indexes using the Shannon-Weaver Information Measure (Shannon and Weaver 1949). An index value was calculated for each census in an attempt to detect changes over time in numbers of species and evenness of distribution. Peterson (1975) reported species diversity indexes from throughout the United States. The values (a 6-year average) ranged from 2.15 in the south Sonoran Desert to 4.19 in the Cascade Mountains.

Nesting Success Estimates

In 1975 we placed 20 to 22 nest boxes on each of the subplots to increase the number of accessible nests. During the 1976 and 1977 field seasons we found 404 nests on the study plots. Nests were checked periodically to determine clutch size, hatching success, and eventual outcome. Calculations of the probability of success of nest contents were based on nest-days of exposure (Mayfield 1961, 1975). This procedure allows incorporation of incomplete nest records. Green (1977) saw a potential bias in this method; again, however, we feel that if a bias occurs it will be similar in both treatment and control data. Only data from nests that were active at and following treatment were used. To increase the sample size of control tests, we grouped data from control nests into Wallowa

Mountains and Blue Mountains samples for each year. We did not find a sufficient number of nests to allow stratification of the data according to nest type and exposure category. (In the cavity nest category, the majority were mountain chickadees which were utilizing our nest boxes).

The study of nesting success also provided an opportunity to observe bird behavior. Parent birds were observed at the nest for any abnormal behavior following the application of insecticides. A casualty search, which may best be described as a "random walk," was also conducted regularly on all plots in 1976 and 1977; the hours of effort were recorded.

Brain Cholinesterase Studies

The materials and methods used for the cholinesterase (ChE) studies are described by Zinkl and others (1979).

Brain ChE inhibition of 50 percent was considered diagnostic for cause of death by Ludke and others (1975), although there is some difference of opinion among investigators (Zinkl and others 1977). Following Ludke and others (1975), we have used a 20-percent depression as indicative of exposure, although we believe that more research should be conducted to precisely correlate depression levels with actual mortality. We collected birds for measurement of brain ChE activity on the portion of the spray areas (48.6 ha) where birds were not censused. Recognition of symptoms of ChE inhibition was important for accurate interpretation of bird behavior during the field investigation. Signs of poisoning that would have been noticeable in the field or with trapped birds in hand include miosis, salivation, lacrimation (muscurinic effects), muscle twitching, dyspnea, paralysis, and clonic convulsions (nicotinic effects) (Zinkl and others 1977).

Plot Comparability Tests

As a means of evaluating comparability between control plots and treated plots, similarity indexes were calculated to compare bird communities. An index value of 1.0 would indicate that two plots shared exactly the same species and that a particular species had the same relative abundance and the same relative frequency in both plots. Although according to Moulding (1976) no objective criterion exists for assessing similarity with this index, we feel that a realistic value for high similarity can be determined. To do this, we divided alternate censuses on a 1977 control plot into two parts and calculated a similarity index to compare these parts. In essence, this index compared the community with itself. The resulting index value was 0.90. On this basis, we judged that the range we found for treatment and control plots, 0.66 to 0.81, was high enough to make the comparisons meaningful.

Similarity indexes were also calculated to compare bird communities on the same plot between the two years. These values ranged from 0.73 to 0.82, suggesting that the basic community structure changed very little between years.

RESULTS AND DISCUSSION

We did not find any sick or dead birds, or observe any abnormal behavior in birds on the plots treated with Dimilin or Sevin-4-Oil in 1976 or 1977. On plots treated with Orthene, however, several birds showed abnormal activity. One day following application of 1.12 kg/ha, we captured a warbling vireo that was salivating profusely, a symptom of organophosphate poisoning. The bird was collected for measurement of brain cholinesterase activity, which was 38 percent below normal (see ChE discussion later). Three days following application on the same plot, we observed an American robin having difficulty maintaining its balance on perches (incoordination is also a symptom of organophosphate poisoning). The bird fell from its perch several times, and once teetered over until it clung upside down from its perch. It then fell and either flew or glided out of sight where it could not be located. We did not find any dead birds on the plot treated with Orthene at 1.12 kg/ha or its control plot in 1976 or 1977.

On the plot treated with Orthene at 2.24 kg/ha, 20 days following application, we captured an adult male ruffed grouse that was unable to fly. The bird was not emaciated, but showed incoordination. On July 21, an adult male ruffed grouse was found dead about 130 m from the site where the sick grouse had been released 6 days earlier. No sick or dead birds were found on any control plots in 1976, or on any plots in 1977.

Population Composition

Breeding Pairs

We examined the estimates of breeding pairs at three levels—individual species, exposure categories, and total species. Detailed findings are presented in the Appendix table.

No major changes in total numbers of breeding pairs occurred immediately following spray on plots treated with Dimilin, Sevin-4-Oil, or Orthene in 1976. Total numbers of breeding pairs, however, did decrease slightly on most subplots—both treatment and control. These decreases were probably due to the completion of nesting cycles of some species. The greatest 1976 postspray decreases in individual species were noted for the warbling vireo and yellow-rumped warbler on the plot treated with Orthene at 1.12 kg/ha.

The warbling vireo is known to sing throughout the breeding season (Sutton 1949), so detectability of the species should not have changed following treatment unless its behavior was affected. Observations of warbling vireo nests on other subplots in 1976 and 1977 indicated that nesting cycles of the species did not terminate until mid-July, 3 weeks after insecticide treatment. Mortality unrelated to the insecticide may have occurred; however, the possibility of treatment effects cannot be excluded. Numbers of warbling vireos were steady or down slightly in other plots.

The apparent decrease observed in the yellow-rumped warbler on the two Orthene-treated plots may also have been related to the insecticide. In the two Orthene plots, the yellow-rumped warbler declined from 7 to 4 breeding pairs, while numbers in the two controls held steady (7 and 7). Furthermore, numbers on the remaining plots also held steady (15 and 16 pairs). Interpretation of recorded detections of this abundant species was very difficult. Territories were not well defined, perhaps because of the presence of surplus males that were not restricted to a given territory (Stewart and Aldrich 1951), wide-ranging movements, a reduction of vocal activity as the breeding season progressed, or inability of observers to detect simultaneous singing. In contrast to the yellow-rumped warbler, the Townsend's warbler showed an increase in the two Orthene plots (8 to 11 pairs) compared to its controls (8 and 8), and decreased slightly in the remaining plots (15 to 12 pairs).

Between 1976 and 1977, on one of the subplots treated with Sevin-4-Oil at 2.24 kg/ha, decreases occurred in the number of breeding pairs of open-nesters with medium exposure to falling spray. The overall reduction (24 or 25 to 17 pairs) was most evident in the western tanager (4 to 0 pairs). Similar reduction also occurred in the golden-crowned kinglet and lazuli bunting on the subplot treated with Dimilin at 0.28 kg/ha, in the Swainson's thrush on several treatment and control subplots, and in the warbling vireo on all subplots.

Increases from 1976 to 1977 in total breeding pairs occurred on both subplots treated with Dimilin (0.14 and 0.28 kg/ha) and their control (Burn Creek). These increases were most evident in the American robin (control), the Townsend's and MacGillivray's warbler (Dimilin 0.14 kg/ha), and the mountain chickadee (Dimilin 0.28 kg/ha). Mountain chickadees also increased on the Whiskey Creek control subplot and the subplots sprayed with Sevin-4-Oil at 2.24 kg/ha (Lower Goose Creek). Increases in mountain chickadees were due primarily to increased use of nest boxes.

Bird populations of western coniferous forests are known to undergo marked fluctuations in density (Wiens 1975). In Utah, Samson (1976) recorded a 16-fold increase in the size of a Cassin's finch population from 1971 to 1972, followed by a 9-fold increase from 1972 to 1973. In a ponderosa pine forest in central Oregon, between-year densities of the mountain chickadee and brown creeper increased 81 and 78 percent, respectively (Gashwiler 1977). Because many of the between-year changes we observed in breeding pairs also occurred on control subplots, we conclude that most such changes probably reflect normal population fluctuations. Another possible source of fluctuations on the plots treated with Dimilin and Sevin-4-Oil, and their control plots, may be the change in observers between years.

Fixed-Station Bird Count

Trends in mean numbers of birds per station (all species) on treatment plots were similar to those on control plots for each of the three insecticides in both 1976 and 1977 (see Appendix for graphs of these data). However, comparisons based on all species may not be valid, because counts for species not common to both treatment and control plots could mask a decline in one, or even several species on treated plots. Therefore we compared trends in mean numbers of birds per station based on species common to both treatment and control plots. Results were essentially the same as those derived from comparisons of all species.

A confidence interval (95 percent level) was calculated for each census as a method of comparing data means from the 14 stations (*fig. 2,* Appendix). We attributed most of the within-census variation to lack of homogeneity in habitat from station to station. There were also fluctuations in mean numbers of birds per station between censuses on the same study plots. Changes in bird behavior at different stages of the nesting cycle and variations in bird activity due to changing weather conditions accounted for much of the between-census variation.

Trends in the mean numbers of birds per station were also examined for each nest-type and exposure category. We found no major differences, on either treatment or control plots, between mean numbers of open-nesters with high exposure to spray, for any of the three insecticides in either 1976 or 1977 (see Appendix). Trends of other nest-types and exposure categories were similar to those obtained for open-nesters with high exposure to spray.

Although numbers of individuals of most species were too few for separate evaluation, we examined several of the more abundant species and found no apparent differences in numbers between treatment and control plots following application of any of the three insecticides. Species examined on the plots treated with Dimilin and Sevin-4-Oil were *Empidonax* sp. (dusky and Hammond's flycatchers, combined because they are sibling species difficult to separate), mountain chickadee, western tanager, pine siskin, dark-eyed junco, and chipping sparrow. Species examined on the plots treated with Orthene were mountain chickadee, yellow-rumped warbler, Townsend's warbler, pine siskin, and dark-eyed junco.

Mean numbers of birds per station (all species) were generally greater in 1977 than in 1976 on each of the plots treated with Dimilin and Sevin-4-Oil. We believe that these increases were due to slight variations in observer methodology. To determine if any changes in bird abundance were real, we calculated a ratio (treatment plot/control plots) of mean numbers of birds per station (all species) for postspray census periods in each year *(table 2).* The greatest percentage change in ratios between years on any plot was 13 percent. We believe these changes represented small fluctuations in bird abundance and could easily be attributed to normal yearly variations in bird populations. Plots treated with Orthene were censused by the same observers in 1976 and 1977; no large fluctuations in bird abundance were noted between years.

Table 2—*Ratio*[1] *of bird population on treatment plots to that on control plots, for postspray census periods, 1976 and 1977*[2]

Treatment	Population ratio		Percent difference
	1976	1977	
Sevin-4-Oil			
Lower Goose Creek	0.95	1.00	+5
Sevin-4-Oil			
Lower Lick Creek	0.86	0.77	−10
Dimilin			
0.14 kg/ha	1.14	0.99	−13
0.28 kg/ha	1.02	1.01	−1

[1] Based on mean number of birds per station (treatment/control).

[2] Period extended from late June through mid-July for both years.

Species Diversity

Trends in species diversity on treatment plots were similar to those on control plots for all three insecticides in both pre- and postspray periods, 1976, and in the census period of 1977 (Appendix). Diversity index values were generally stable throughout each field season and ranged between 2.5 and 3.0. These data indicated that no large changes in species diversity occurred following the application of any of the three insecticides.

Nesting Success

In northeastern Oregon, insecticides for control of the Douglas-fir tussock moth are most effective when applied in late June. In the present study, treatment plots were sprayed at this time to simulate conditions of an actual control program. The spray period coincided with the peak of hatching of young birds on all study plots *(fig. 4).* Lack (1968, p. 303) stated that for many birds "breeding is timed in relation to the availability of food for the young." Consequently, insecticides applied at the peak of hatching potentially affect the ultimate success of nests by (1) reducing the number of insects during a period when they are in great demand as a source of food, and (2) contaminating food (primarily insects) ingested by parent birds and nestlings. If insecticide particles remain suspended in the air for any length of time, then they also are potentially hazardous, by inhalation, to parent birds and nestlings. In short, the optimum time for insecticide treatment is also a period of great vulnerability for forest birds (DeWeese and others 1979).

The calculations of overall probabilities of success of all nest contents (see Methods section)

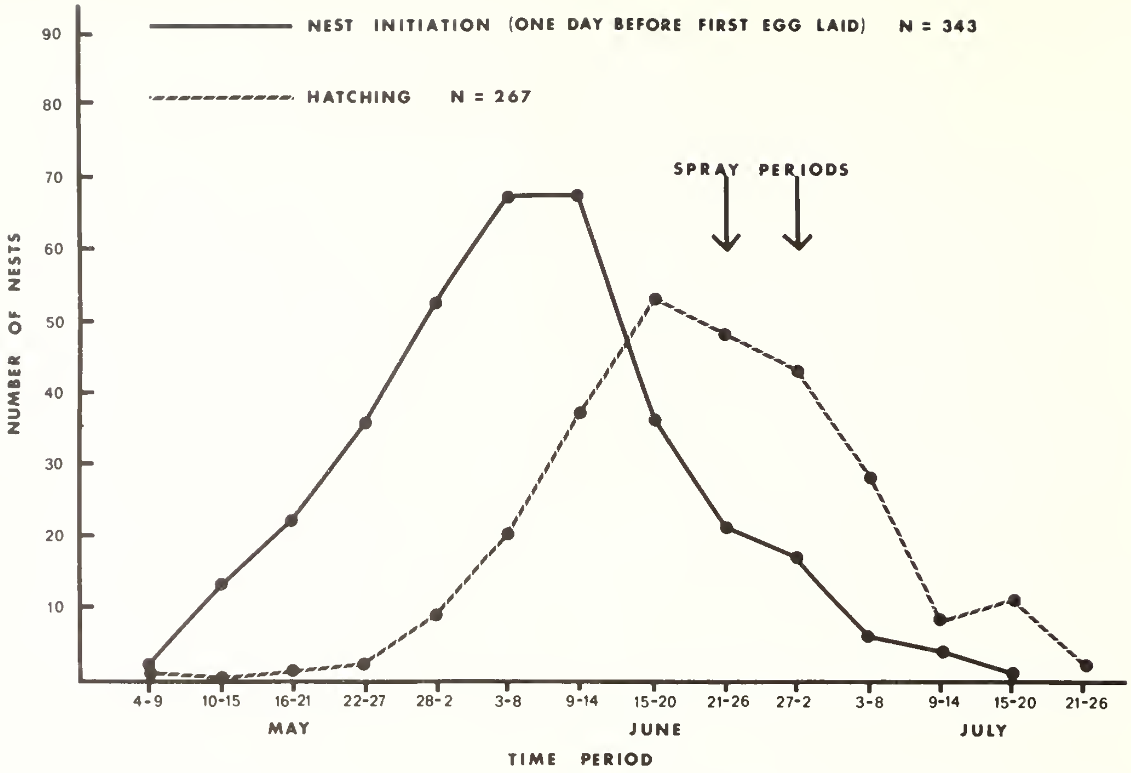


Figure 4—Phenology of nests located on all study plots in 1976 and 1977 is shown in relation to dates of spraying with Sevin-4-Oil, Dimilin, and Orthene.

showed that in 1976 nesting success on the plot treated with Dimilin (0.28 kg/ha) and the plots treated with Sevin-4-Oil (2.24 kg/ha) was 16 and 14 percent less likely, respectively, than on the combined Wallowa Mountains control plots *(table 3)*. Success of nest contents on the plot treated with Orthene (1.12 kg/ha) was 7 percent less likely than on the combined Blue Mountains control plots. We do not know if these differences represent actual changes or if they merely reflect variations resulting from insufficient sample sizes of nests, or variable species composition of the samples. Nice (1957) showed that nesting success varied among species, especially between cavity- and open-nesting species.

In 1977, overall likelihood of success *(table 3)* on the Wallowa Mountains control plots decreased 10 percent from 1976; on the plot treated with Dimilin (0.28 kg/ha) and plots treated with Sevin-4-Oil it increased 17 and 23 percent, respectively. Probability of success on the Blue Mountains control plots increased 9 percent from 1976 to 1977; on plots treated with Orthene (1.12 or 2.24 kg/ha) it either remained the same or decreased by 15 percent. These fluctuations tend to support the view that changes of 10 to 15 percent may reflect normal biological variability rather than insecticide effects.

Because nest records were few for individual species, calculation of probability of success was based on a combination of all species. Species composition was similar between treatment and control plots, however.

Brain Cholinesterase

Depression of brain cholinesterase (ChE) activity has been used previously as an indicator of organophosphate and carbamate poisoning in birds (Stickel 1974, Ludke and others 1975, Zinkl and others 1977). Fifteen species (134 birds) were collected in unsprayed areas for use as controls. No birds were collected on plots treated with Dimilin because, to our knowledge, it does not inhibit ChE. Results of the ChE analyses are reported by Zinkl and others (1979), and will be discussed only briefly here.

Table 3—*Probability of success for nests active during postspray census periods, 1976 and 1977*[1]

Treatment	Probability of success	Nests	1976 Total nest days	Nest type		Probability of success	Nests	1977 Total nest days	Nest type	
				Open	Cavity				Open	Cavity
	Percent			*Percent*		*Percent*			*Percent*	
Sevin-4-Oil[2] (2.24 kg/ha)	45	30	435.5	80	20	68	34	632.5	61.8	38.2
Dimilin (0.14 kg/ha)	69	11	158	81.8	18.2	66	24	274.5	87.5	12.5
Dimilin (0.28 kg/ha)	43	15	183	80	20	60	15	290	66.7	33.3
Wallowa Mtns. control plots	59	27	392.5	77.8	22.2	49	34	524.5	70.6	29.4
Orthene (1.12 kg/ha)	44	8	101	87.5	12.5	44	12	185	75	25
Orthene (2.24 kg/ha)	52	8	101	100	0	37	13	212	76.9	23.1
Blue Mtns. control plots	51	11	167	72.7	27.3	60	25	519	60	40

[1] Period extended from late June through mid-July for both years.

[2] Nests from the Lower Goose Creek plot and the Lower Lick plot were combined.

Sevin-4-Oil

During the summer of 1976, we collected nine passerine species from plots treated with Sevin-4-Oil. The only birds showing ChE inhibition were two Cassin's finches collected 1 day following spray; their ChE activities were depressed 23 and 27 percent. No birds collected on succeeding days showed depression. These findings might be attributed to the rapidly reversible action of carbamates on cholinesterase activity. Carpenter and others (1961) reported that rat brain cholinesterase returned to near-normal levels 24 hours after carbaryl treatments. For a general discussion of the reversible action of carbamates on cholinesterase activity see Matsumura (1975, p. 153-154).

Orthene

In marked contrast, Orthene caused extensive depression of brain ChE activity. Depression levels of 30 to 50 percent were commonly recorded for 11 of 12 species collected after insecticide treatment. On the plot treated with 1.12 kg/ha, 45 of 65 birds collected 1 to 33 days following spray displayed the ChE inhibition. The highest frequency of depression (12 out of 13 birds or 92 percent) was noted on the second day following spray. The greatest depression for any birds on the plot treated with 1.12 kg/ha was 65 percent. All birds collected 1 to 6 days postspray on the plot treated with 2.24 kg/ha showed ChE inhibition; the greatest reduction was 54 percent. Thus, some birds on plots treated with Orthene may have been subject to fatal organophosphate poisoning.

During the summer of 1977 (1 year postspray), 11 birds (6 species) were collected on the plot treated with Orthene at 1.12 kg/ha. The brain ChE activities from all samples were within the normal range.

CONCLUSIONS

Our study was a necessary step in testing the effects of Dimilin, Sevin-4-Oil, and Orthene on forest birds in a field situation. Certain limitations of the study affected our ability to interpret the data, however. Comparisons of bird populations between pre- and postspray periods were complicated by (1) movements of birds into and out of the small treated plots, (2) the presence of floating surplus individuals within the study plots, and (3) variability in numbers of birds detected, because bird behavior changed with weather conditions and at different stages of the nesting cycle. The fact that the same observers could not be used in both 1976 and 1977 on several plots affected comparisons of bird populations between years. Because replications of study plots were not possible, no analysis of variance of our data could be made; consequently, interpretation of the results was partly subjective. Because of these limitations, our census methods may not have been sensitive enough to detect subtle changes.

Timing of insecticide applications simulated that of an actual control program; however, our study area was not infested with tussock moth. If ingestion of sick or dying tussock moths is one route through which birds encounter pesticides, then the low abundance or absence of moths on the study plots may have influenced our findings.

Some of the problems we encountered are inherent initial difficulties in most field studies of birds. Solutions to some of these are discussed under "Recommendations." Our findings as compared to those of other investigators will now be examined.

Dimilin

From the results of our population censuses, nesting studies, and observations of bird behavior, we did not detect any adverse effects of Dimilin (at 0.14 and 0.28 kg/ha) on forest birds in our study. Buckner and others (1975) and Bart (1975) reported similar findings.

Sevin-4-Oil

We detected no major effects on forest birds from applications of Sevin-4-Oil at 2.24 kg/ha. Our population findings are in agreement with those of Connor (1960), Doane and Schaeffer (1971), and McEwen and others (1972), but conflict with those of Moulding (1976). Moulding detected a 55-percent decrease in bird populations following two applications of Sevin (at 1.12 kg/ha) on a 2000-ha spray block in a New Jersey deciduous forest. There were important differences, however, between our study and Moulding's:

1. His study coincided with a gypsy moth outbreak, whereas ours had no insect outbreak.
2. His study was associated with a large spray block (2000 ha), whereas ours was only 129.5 ha.
3. His spray was applied at two different times, whereas ours was a single application.

Moulding's spray treatment thus may have been considerably more effective than ours in altering avian foods and exposing birds to pesticides. It may not have been possible for birds to get out of his sprayed area on a temporary basis. In other words, birds left permanently if they were avoiding food shortage or insecticide exposure, whereas in our study, they could have utilized unsprayed surrounding areas for feeding while maintaining territories or nests within the sprayed plots. This line of investigation deserves further study.

DeWeese and others (1979) also conducted an investigation during an actual infestation and suppression program (spruce budworm). They detected no major effects on bird populations resulting from an application of Sevin-4-Oil at 1.12 kg/ha (one-half the rate used in Moulding's study), but the plots were somewhat smaller (350 to 500 ha).

Orthene

The admittedly limited census data suggest that a decrease in the number of breeding pairs of the warbling vireo and yellow-rumped warbler may have occurred following application of Orthene at 1.12 kg/ha. Because warbling vireos were not nesting in the 2.24 kg/ha plot, we have no related data; however, we know that the yellow-rumped warbler numbers also decreased in the 2.24 kg/ha plot. These decreases cannot be attributed to variations in the known breeding habits and behaviors of the two species.

Our findings on brain ChE activity for plots treated with Orthene, and our observations of abnormal behavior, symptomatic of organophosphate poisoning, are of interest here. Location of a dead grouse on the plot treated with 2.24 kg/ha may be indicative of greater overall mortality, considering the rapidity with which carcasses disappear due to heat, predators, or scavengers (Davis 1970). In a study of quail remains, Rosene and Lay (1963) concluded that the location of even a small number of carcasses is reason to suspect a rather heavy mortality.

Our observations thus indicate that the application of Orthene at 1.12 kg/ha and 2.24 kg/ha can cause sickness and possibly death in forest birds. Our findings differ from those of Buckner and McLeod (1975) who reported that applications of 0.56 kg/ha and 1.4 kg/ha had no detectable effect on forest birds in Ontario. However, Buckner and McLeod's study was limited by the small size of the study areas (4 ha), the single census method (spot-mapping), the short period of censusing (5 days before and 5 days after spray), and the absence of ChE analyses. We believe that further tests, especially for Orthene, must be made on larger study areas, with an insect outbreak, and with a replicated design.

RECOMMENDATIONS

Before an insecticide can be registered for use, initial laboratory screening and safety tests, field tests, and pilot control studies must take place. Our field tests represent the second step in the process, and the first stage of study of the effects on nontarget organisms in an actual forest environment. In further testing, because funds and manpower are limited, priority must be given to the most sensitive research methods, as described below.

Field Tests

Studies of Brain Cholinesterase Activity

(Specific for effects of organophosphate and carbamate insecticides.) This is the most sensitive and most easily obtained indicator of effects of certain insecticides. Additional work is critically needed, however, to relate ChE depression to the mortality of wild birds. Because ChE depression may result from ingestion of poisoned target insects, we believe priority should be given to conducting field tests in areas with insect outbreaks. Additionally, the spray areas should be as large as possible to minimize edge effects.

Nesting Studies

These can provide a sensitive measure of pesticide effects, given sufficient sample sizes of nests and replications of treatments. Location of as many nests as possible is important to ensure adequate sample size. Laughlin and Lundy (1976), in a study of pesticide effects on hatchability, provide an equation that relates a difference between treatments to the sample size of eggs required to detect that difference. Once nests are found, standarized techniques should be used by all observers to ensure that the same kinds of information are recorded for all nests. Nests should be checked regularly to provide adequate coverage of all phases of the nesting cycle, and nest contents should not be unnecessarily handled or disturbed when checked. Certain nests, particularly ground nests, are much more vulnerable to predation as a result of human visits (Bart 1977), and should be approached in such a way as to minimize disturbance of the immediate area. Studies of nesting activities also afford an excellent opportunity to make behavioral observations of adult forest birds. In future studies covering larger areas, more effort should be made to obtain meaningful information at the species level. We believe nesting success information is probably the most meaningful biological field data that can be collected: if a parent bird is sick or dead and therefore cannot care for its eggs or young, obviously nesting success will be reduced. Also, nesting success may be reduced by the direct effects of the sprays on the young. Thus, the possible adverse reactions of the adults and/or the young to forest sprays may be detected with nesting studies.

Observations of Bird Behavior

These can be effective indicators of the effects of insecticides. A knowledge of symptoms of poisoning caused by the insecticides under investigation is valuable for accurate interpretation of bird behavior. Incoordination and salivation were both observed during our study. A regular schedule of casualty searches should also be followed on both treatment and control plots to obtain an index of mortality (for example, casualties per hour of search).

Censuses of Populations

If sufficient time remains, these should be conducted on both treatment and control plots. If standard census methods for determining avian abundance (spot-mapping, line transects, fixed station censuses) are selected, the advantages and disadvantages of the methods should be considered. However, we believe potential problems with repopulation from the "floating surplus" limit the value of all live bird census techniques.

Two approaches were explored in this study and a discussion of the spot-map method as opposed to the fixed-station census seems warranted here.

Advantages

- Allows more familiarity with individual birds and therefore may detect subtle changes in behavior or the loss of an individual bird. (Losses of birds in the Orthene plot were detected by the spot-map method.)
- May detect replacement birds because a new bird probably will not take the exact territory of the bird it replaced (it may, however, if only one bird of the pair was lost).

Disadvantages

- The analytical procedure is somewhat subjective and provides only one population estimate for a period of interest, and no statistics, to our knowledge, can be applied to the data. A short-term loss is difficult to detect by the procedures used (counts over a period of days or weeks are used to make one population estimate).

- Requires a considerable amount of lead time to establish the plots and at least eight censuses per plot are recommended.

We found one major disadvantage of both methods —because we were unable to recognize individual birds, we could not detect the replacement of local breeding birds by the "floating surplus" birds. Ideally, a study designed to capture, mark, and observe individual birds of several species might be an effective way to determine effects of a spray project, but practical difficulties must be considered:

Handling of birds during early stages of the nesting season may adversely influence their nesting activities.

If the effects of insecticides are species-specific (related to species tolerance and exposure to falling spray), then the examination of a few select species (usually the most numerous and most trappable) may lead to erroneous conclusions.

The number of manhours required to capture and monitor reasonably large numbers of individually marked birds may be prohibitive.

Because of these limitations, we do not recommend an individual marking study in the initial attempts to evaluate a spray project. After problems have been detected with an individual species, this approach may provide the refinement needed. Perhaps a more meaningful approach would be a mass marking of the breeding birds on the study area by aerially applied fluorescent particles or dye at the time of spraying. Then, the birds in the area at the time of spray would be recognizable. Recognition is particularly important in studies of mobile birds on small areas. Basic research on this subject is underway at the Denver Wildlife Research Center of the U.S. Fish and Wildlife Service.

For initial field testing, ideally both spot-mapping and fixed-station indexes of relative abundance can be used. If plot replications are not feasible, we believe more useful information would be obtained from the spot-map method. We do not plan to conduct additional field studies, however, without at least three replications of both treatments and controls. In conclusion, it should be noted that live bird censuses have received the lowest priority among our recommendations for future investigations—primarily because of the repopulation problems.

Pilot Control Study

The same priorities described for field tests should be followed in designing a pilot control study of the effects of insecticides on forest birds. Because the size of the treated area in the pilot control study is usually larger than it is in a field test, there is less likelihood of edge effect. A larger study area can also cover more habitat types, thus expanding coverage of species and providing more opportunity to stratify a data-gathering program according to similar avian communities.

LITERATURE CITED

American Ornithologists' Union.
1957. **Check-list of North American birds,** 5th ed. Baltimore, Maryland. 691 p.

American Ornithologists' Union.
1973. **Thirty-second supplement to the American Ornithologists' Union check-list of North American birds.** Auk 90(2):411-419.

American Ornithologists' Union.
1976. **Thirty-third supplement to the American Ornithologists' Union check-list of North American birds.** Auk 93(1):875-879.

Bart, J.
1975. **The effects of Dimilin on birds.** *In* Forest insect and disease management/evaluation report (The environmental impact of Dimilin (TH6040) on a forest and aquatic ecosystem.). Expanded Gypsy Moth Research and Applications Program. Lotel Report 210. p. 48-82.

Bart, J.
1977. **Impact of human visitations on avian nesting success.** Living Bird 16:187-192.

Bray, J. R., and J. T. Curtis.
1957. **An ordination of the upland forest communities of southern Wisconsin.** Ecol. Monogr. 27:325-349.

Buckner, C. H., and B. B. McLeod.
1975. **Impact of aerial applications of Orthene upon non-target organisms.** Can. For. Serv., Dep. Environ. Rep. CC-X-104. Chem. Control Res. Inst., Ottawa, Ontario. 48 p.

Buckner, C. H., B. B. McLeod, and P. D. Kingsbury.
1975. **The effect of an experimental application of Dimilin upon selected forest fauna.** Can. For. Serv., Dep. Environ. Rep. CC-X-97. Chem. Control Res. Inst., Ottawa, Ontario. 26 p.

Carpenter, C. P., C. S. Weil, P. E. Palm, M. W. Woodside, J. H. Nair III, and H. F. Smyth, Jr.
1961. **Mammalian toxicity of 1-naphthyl-N-methylcarbamate (Sevin insecticide).** J. Agric. Food Chem. 9(1):30-39.

Connor, P. F.
1960. **A study of small mammals, birds and other wildlife in an area sprayed with Sevin.** N.Y. Fish Game J. 7(1):26-32.

Davis, D. E.
1970. **Evaluation of techniques for measuring mortality.** J. Wildl. Dis. 6:365-375.

DeWeese, L. R., C. J. Henny, R. L. Floyd, K. A. Bobal, and A. W. Schultz.
1979. **Response of breeding birds to aerial sprays of trichlorfon (Dylox) and carbaryl (Sevin-4-Oil) in Montana forests.** U.S. Fish. Wildl. Serv. Spec. Sci. Rept.—Wildl. 224. 29 p.

Doane, C. C., and P. W. Schaeffer.
1971. **Aerial application of insecticides for control of the gypsy moth: with studies of effects on non-target insects and birds.** Conn. Agric. Exp. Stn. Bull. 724. 23 p.

Franklin, J. F., and C. T. Dyrness.
1973. **Natural vegetation of Oregon and Washington.** USDA Forest Serv. Gen. Tech. Rep. PNW-9. Pacific Northwest For. and Range Exp. Stn., Portland, Oreg. 417 p.

Gashwiler, J. S.
1977. **Bird populations in four vegetational types in central Oregon.** U.S. Fish Wildl. Serv. Spec. Sci. Rep.—Wildl. 205. 20 p.

Graham, D. A., J. Mounts, and D. Almas.
1975. **1974 cooperative Douglas-fir tussock moth control project. Oregon. Washington. Idaho.** Pacific Northwest Region, Forest Serv., U.S. Dep. Agric., Portland, Oreg. 74 p.

Green, R. F.
1977. **Do more birds produce fewer young? A comment on Mayfield's measure of nest success.** Wilson Bull. 89(1):173-175.

Hall, G. A.
1964. **Breeding-bird censuses—why and how.** Audubon Field Notes 18(3):413-416.

Lack, D.
1968. **Ecological adaptations for breeding in birds.** Methuen and Co., London. 409 p.

Laughlin, K. F., and H. Lundy.
1976. **The influence of sample size on the choice of method and interpretation of incubation experiments.** Brit. Poult. Sci. 17:53-57.

Ludke, J. L., E. F. Hill, and M. P. Dieter.
1975. **Cholinesterase (ChE) response and related mortality among birds fed ChE inhibitors.** Arch. Environ. Contam. Toxicol. 3(1):1-21.

Matsumura, F.
1975. **Toxicology of insecticides.** Plenum Press, New York. 503 p.

Mayfield, H. F.
1961. **Nesting success calculated from exposure.** Wilson Bull. 73(3):255-261.

Mayfield, H. F.
1975. **Suggestions for calculating nest success.** Wilson Bull. 87(4):456-466.

McEwen, L. C., C. E. Knittle, and M. L. Richmond.
1972. **Wildlife effects from grasshopper insecticides sprayed on short-grass range.** J. Range Manage. 25(3):188-194.

Moulding, J. D.
1976. **Effects of a low-persistence insecticide on forest bird populations.** Auk 93(4):692-707.

Nice, M. M.
1957. **Nesting success in altricial birds.** Auk 74: 305-321.

Peterson, S. R.
1975. **Ecological distribution of breeding birds.** *In* Proceedings of the Symposium on Management of Forest and Range Habitats for Nongame Birds. USDA Forest Serv. Gen. Tech. Rep. WO-1, p. 22-38, Washington, D.C.

Robbins, C. S.
1963. **Bird census by two methods.** *In* Pesticides—Wildlife Studies: A Review of Fish and Wildlife Service investigations during 1961 and 1962. p. 85. U.S. Fish and Wildlife Service. Circular 167. 109 p.

Robbins, C. S.
1970. **Recommendations for an international**

standard for a mapping method in bird census work. Audubon Field Notes 24:723-726.

Rosene, W., Jr., and D. W. Lay.
1963. **Disappearance and visibility of quail remains.** J. Wildl. Manage. 27(1):139-142.

Samson, F. B.
1976. **Territory, breeding density, and fall departure in Cassin's finch.** Auk 93(3):477-497.

Shannon, C. E., and W. Weaver.
1949. **The mathematical theory of communication.** Univ. Ill. Press, Urbana. 117 p.

Stewart, R. E., and J. W. Aldrich.
1951. **Removal and repopulation of breeding birds in a spruce-fir forest community.** Auk 68(4):471-482.

Stickel, W. H.
1974. **Effects on wildlife of newer pesticides and other pollutants.** Proc. West. Assoc. State Game and Fish Comm. 53:484-491.

Sutton, G. M.
1949. **Studies of the nesting birds of the Edwin S. George Reserve. Part I. The vireos.** Univ. Mich. Mus. Zool. Misc. Publ. 74, 37 p.

Wickman, B. E., R. R. Mason, and C. G. Thompson.
1973. **Major outbreaks of the Douglas-fir tussock moth in Oregon and California.** USDA Forest Serv. Gen. Tech. Rep. PNW-5, 18 p. Pacific Northwest Forest and Range Exp. Stn., Portland, Oreg.

Wiens, J. A.
1975. **Avian communities, energetics, and functions in coniferous forest habitats.** *In* Proceedings of the Symposium on Management of Forest and Range Habitats for Nongame Birds. USDA For. Serv. Gen. Tech. Rep. W0-1, p. 226-265. Washington, D.C.

Williams, A. B.
1936. **The composition and dynamics of beech-maple climax community.** Ecol. Monogr. 6:318-408.

Wright, K. H. (ed.).
1977. **The Douglas-fir tussock moth research and development program (ESA Symposium).** Bull. Entomol. Soc. Amer. 23(3):167-180.

Zinkl, J. G., C. J. Henny, and L. R. DeWeese.
1977. **Brain cholinesterase activities of birds from forests sprayed with trichlorfon (Dylox) and carbaryl (Sevin-4-Oil).** Bull. Environ. Contam. Toxicol. 17(4):379-386.

Zinkl, J. G., C. J. Henny, and P. J. Shea.
1979. **Brain cholinesterase activities of passerine birds in forests sprayed with cholinesterase inhibiting insecticides.** *In* Animals as monitors of environmental pollutants. p. 356-365. Nat. Acad. Sci., Washington, D.C.

Species Check List

Common and scientific names of all species recorded on each study plot are given here. Species are grouped by nest type and exposure category and are listed in taxonomic order. Taxonomic nomenclature for all bird species follows that of the American Ornithologists' Union (1957, 1973, 1976).

Open-Nest Species With High Potential Exposure to Spray

Spotted sandpiper	*Actitis macularis*
Blue grouse	*Dendragapus obscurus*
Mourning dove	*Zenaida macroura*
Turkey vulture	*Cathartes aura*
Red-tailed hawk	*Buteo jamaicensis*
Golden eagle	*Aquila chrysaetos*
Common nighthawk	*Chordeiles minor*
Vaux's swift	*Chaetura vauxi*
Calliope hummingbird	*Stellula calliope*
Olive-sided flycatcher	*Nuttalornis borealis*
Western wood pewee	*Contopus sordidulus*
Willow flycatcher	*Empidonax traillii*
Dusky flycatcher	*Empidonax oberholseri*
Steller's jay	*Cyanocitta stelleri*
Gray jay	*Perisoreus canadensis*
Common raven	*Corvus corax*
Clark's nutcracker	*Nucifraga columbiana*
Brown-headed cowbird	*Molothrus ater*
Brewer's blackbird	*Euphagus cyanocephalus*
Evening grosbeak	*Hesperiphona vespertina*
Cassin's finch	*Carpodacus cassinii*
Red crossbill	*Loxia curvirostra*
Pine siskin	*Carduelis pinus*
Vesper sparrow	*Pooecetes gramineus*
Chipping sparrow	*Spizella passerina*
Dark-eyed junco	*Junco hyemalis*
Lincoln's sparrow	*Melospiza lincolnii*
Black-headed grosbeak	*Pheucticus melanocephalus*
Lazuli bunting	*Passerina amoena*
Cedar waxwing	*Bombycilla cedrorum*
Warbling vireo	*Vireo gilvus*
Orange-crowned warbler	*Vermivora celata*
Yellow warbler	*Dendroica petechia*
American redstart	*Setophaga ruticilla*
Ruby-crowned kinglet	*Regulus calendula*
Townsend's solitaire	*Myadestes townsendi*
American robin	*Turdus migratorius*

Open-Nest Species With Medium Potential Exposure to Spray

Sharp-shinned hawk	*Accipiter striatus*
Cooper's hawk	*Accipiter cooperii*
Goshawk	*Accipiter gentilis*
Great horned owl	*Bubo virginianus*
Hammond's flycatcher	*Empidonax hammondii*
Song sparrow	*Melospiza melodia*
Fox sparrow	*Passerella iliaca*
Western tanager	*Piranga ludoviciana*
Solitary vireo	*Vireo solitarius*
Yellow-rumped warbler	*Dendroica coronata*
Townsend's warbler	*Dendroica townsendi*
MacGillivray's warbler	*Oporornis tolmiei*
Golden-crowned kinglet	*Regulus satrapa*
Veery	*Catharus fuscescens*

Open-Nest Species With Low Potential Exposure to Spray

Ruffed grouse	*Bonasa umbellus*
Swainson's thrush	*Catharus ustulatus*
Hermit thrush	*Catharus guttatus*
Varied thrush	*Ixoreus naevius*

Cavity-Nest Species

American kestrel	*Falco sparverius*
Pygmy owl	*Glaucidium gnoma*
Belted kingfisher	*Megaceryle alcyon*
Hairy woodpecker	*Picoides villosus*
White-headed woodpecker	*Picoides albolarvatus*
Black-backed three-toed woodpecker	*Picoides arcticus*
Northern three-toed woodpecker	*Picoides tridactylus*
Yellow-bellied sapsucker	*Sphyrapicus varius*
William's sapsucker	*Sphyrapicus thyroideus*
Pileated woodpecker	*Dryocopus pileatus*
Common flicker	*Colaptes auratus*
Cliff swallow	*Petrochelidon pyrrhonota*
Dipper	*Cinclus mexicanus*
Rock wren	*Salpinctes obsoletus*
House wren	*Troglodytes aedon*
Winter wren	*Troglodytes troglodytes*
Brown creeper	*Certhia familiaris*
White-breasted nuthatch	*Sitta carolinensis*
Red-breasted nuthatch	*Sitta canadensis*
Pygmy nuthatch	*Sitta pygmaea*
Black-capped chickadee	*Parus atricapillus*
Mountain chickadee	*Parus gambeli*
Western bluebird	*Sialia mexicana*
Mountain bluebird	*Sialia currucoides*

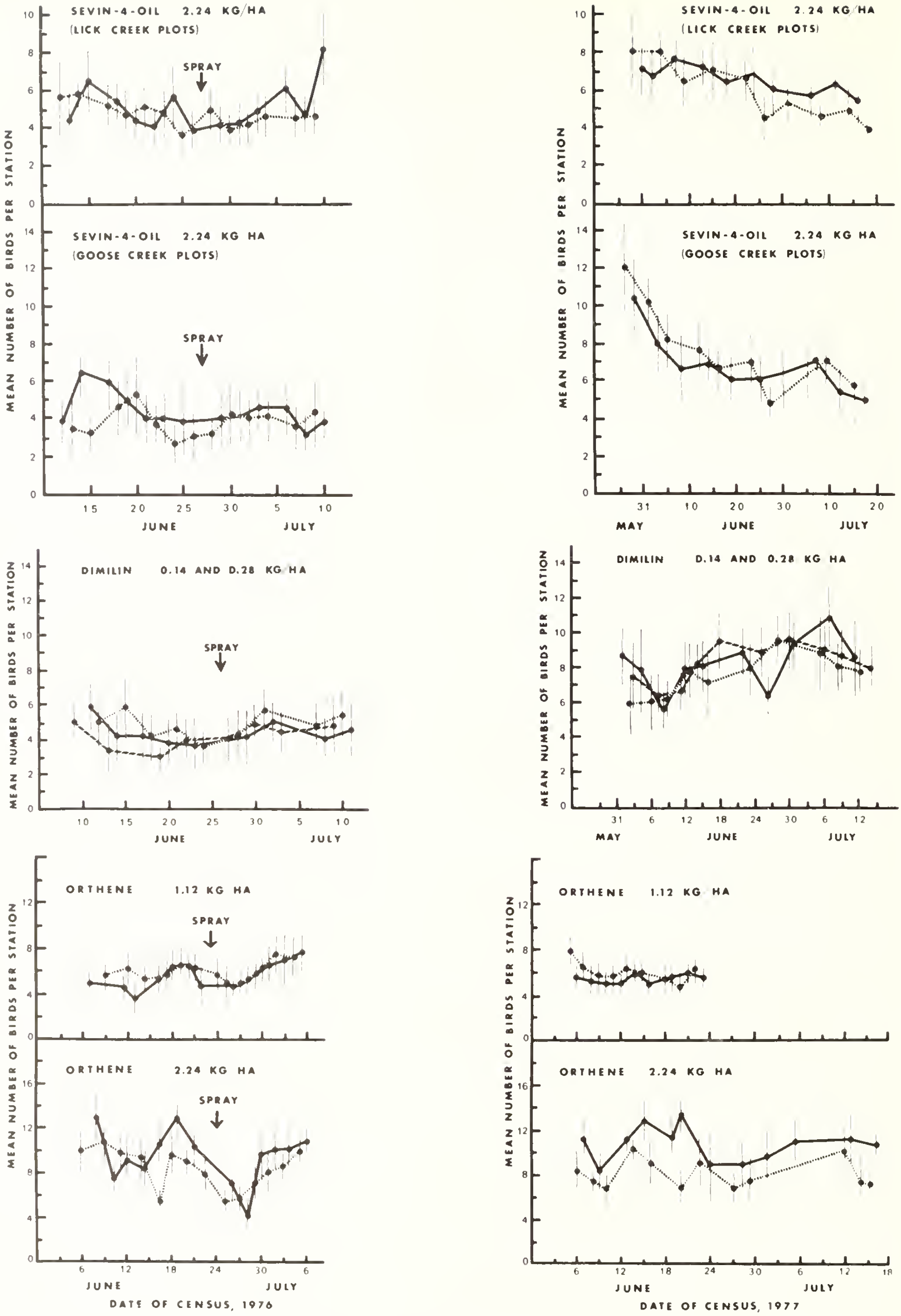


Figure 2—Trends in mean numbers of birds per station (all species) for all study plots during the 1976 (left) and 1977 (right) breeding seasons. Short-dashed lines apply to plots treated with Sevin-4-Oil, Orthene, and Dimilin (0.14 kg/ha); long-dashed lines, Dimilin (0.28 kg/ha); and solid lines, controls. The vertical line at each census date represents a confidence interval (95 percent level).

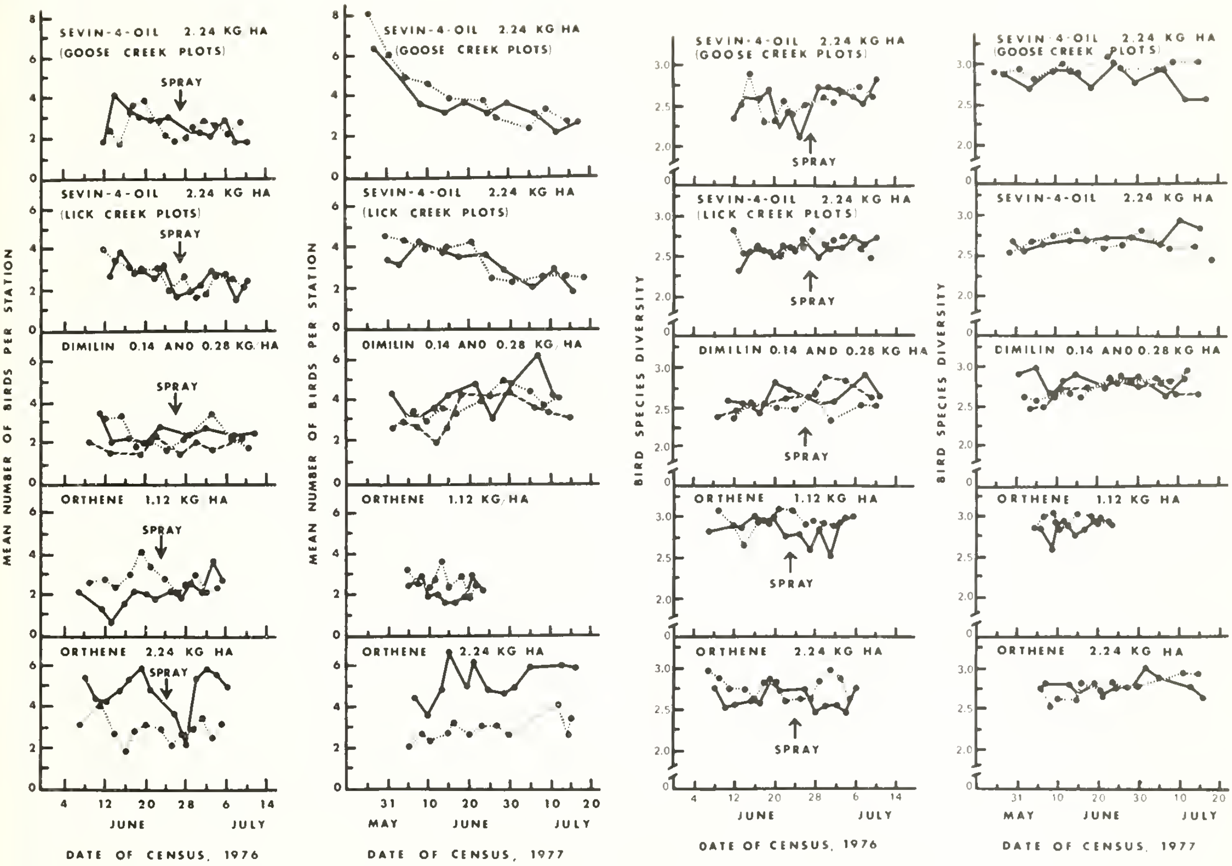


Figure 3—Trends in (left) mean numbers of birds per station (open-nesters with high exposure to spray) and (right) bird species diversity are shown for all study plots in the 1976 and 1977 breeding seasons. Short-dashed lines apply to plots treated with Sevin-4-Oil, Orthene, and Dimilin (0.14 kg/ha); long-dashed lines, Dimilin (0.28 kg/ha); and solid lines, controls. Bird species diversity is expressed as an index (see text).

Table 4—*Estimated numbers of breeding pairs,*[1, 2] *by category of potential*

Species, by exposure category	Dimilin 0.28 kg/ha			Dimilin 0.14 kg/ha			Control Burn Cr.			Sevin-4-Oil 2.24 kg/ha			Cont Upper G	
	1976			1976			1976			1976			1976	
	Pre-spray	Post-spray	1977	Pre-spray	Post-spray	1977	Pre-spray	Post-spray	1977	Pre-spray	Post-spray	1977	Pre-spray	Pos spra
Open-nesting— high exposure														
Spotted sandpiper										1	1	0		
Mourning dove							P	0	1 +	0	P	P		
Willow flycatcher										1	1	2		
Empidonax sp.										7	7	10	8	7
Western wood pewee										P	0	P		
Olive-sided flycatcher														
Gray jay														
Steller's jay	P	0	P				P	P	P	P	0	P		
American robin	1 +	P	1 +	1 +	P	2 +	1 +	1	4	5	5	4	4	3
Townsend's solitaire	0	0	2	P	0	1 +	P	0	1				0	0
Ruby-crowned kinglet	0	0	P	0	0	P				0	0	P		
Warbling vireo	3	3	3 +	3	3	1 +	1	0	1	2 +	2	1	1	1
Orange-crowned warbler							0	0	1	0	0	P		
Yellow warbler										6	5	6	2	2
American redstart										1	1	1		
Black-headed grosbeak	P	0	0							3	3	2	1 +	0
Lazuli bunting	3	3	0	1	1	1 +				2	1	0	P	0
Dark-eyed junco	3	3	4 +	4	4	5	4	3	5 +	2 +	2	1	5	5
Chipping sparrow	3	3	4	3	3	5 +	3 +	3 +	5	5 +	5	4	5	5
Lincoln's sparrow														
Subtotal pairs	13	12	14	12	11	15	9	7	18	35	33	31	26	23
Open-nesting— medium exposure														
Goshawk														
Sharp-shinned hawk										0	P	0		
Hammond's flycatcher	6	6	6 +	6	6	8	1 +	1	3 +					
Veery										3 +	3	3	1	1
Golden-crowned kinglet	3	3	P	1	1	1 +	P	P	P	1	1	1	2	1
Solitary vireo	0	0	2	1	1	3 +	1	1	3	2 +	2 +	1	2	2
Yellow-rumped warbler	3	3	3 +	2	3	3	P	P	2	2 +	2 +	4	4	4
Townsend's warbler	2	2	5	P	0	3	3	3	1	1 +	1	P	2 +	0
MacGillivray's warbler	2	2	4 +	2	2	5	2	3	2	4	5	2	2	2
Western tanager	4	3	4	2	2	2	1	1	P	4	3	P	1	1
Fox sparrow										2	3	3	1	1
Song sparrow										5	5	3 +	1	0
Subtotal pairs	20	19	24	14	15	25	8	9	11	24	25	17	16	12
Open-nesting— low exposure														
Varied thrush				1	0	0							P	P
Hermit thrush	0	0	1 +	0	0	1	0	0	2	0	0	P	1	1
Swainson's thrush	1	3	3	2	3	2 +	1	1	1	2	2	P	2 +	2
Subtotal pairs	1	3	4	3	3	3	1	1	3	2	2	0	3	3
Cavity-nesting														
American kestrel				0	0	P	0	0	1				0	P
Belted kingfisher				0	1	P				0	P	0		
Common flicker	0	0	P	0	0	P	0	0	1	1	1	P		
Yellow-bellied sapsucker	0	0	P	0	0	P				1	1	1		
Williamson's sapsucker							0	0	P					
Hairy woodpecker	0	0	P	0	0	P	0	P	1	0	P	P	0	0
Mountain chickadee	3	3	6 +	2	1	3	3	3	3	2	2	7	3	2
Red-breasted nuthatch							1	1	1 +	0	1	P	0	P
Brown creeper				0	1	0								
House wren										1	1	4		
Winter wren														
Rock wren							2	2	3					
Subtotal pairs	3	3	6	2	3	3	6	6	10	5	6	12	3	2
TOTAL PAIRS	37	37	48	31	32	46	24	23	42	66	66	60	48	40

[1] P = One or more adults observed but no identifiable pairs.

[2] Species not listed unless at least one identifiable pair detected.

[3] See text for explanation of study methods.

+ = Additional adults observed but no identifiable pairs.

spray, on plots treated with three insecticides, and on control plots[3]

n-4-Oil kg/ha		Control Upper Lick Cr.			Orthene 1.12 kg/ha			Control Little Rock Cr.			Orthene 2.24 kg/ha			Control Whiskey Cr.		
		1976			1976			1976			1976			1976		
ost- spray	1977	Pre- spray	Post- spray	1977	Pre- spray	Post- spray	1977	Pre- spray	Post- spray	1977	Pre- spray	Post- spray	1977	Pre- spray	Post- spray	1977
	0															
	9+	4+	4	5	6	5	5									
					P	0	0	1	1	1						
					2	2	2	0	0	1	P	P	0	1	1	1
					0	0	P	P	0	0	P	0	0	1	0	0
	P							P	0	0				1	1	0
+	P	2	2	0	2+	1+	1+	1+	1+	1+	1	1	1+	1+	1	2
	1	P	P	P	P	P	P	P	0	0						
	P	1+	1	3+	0	1+	1+	0	0	1+						
	0	3	2+	P	5	3	4+				P	0	0	2	1	1
	P															
					0	0	P									
+	4	3	2+	2+	2+	2	3	3	5	4+	4	3	4	7	6	8
	3+	3+	2+	3	2	2	1+	0	1	1+	0	0	2	2+	2	4+
					P	0	P	1	0	1						
	17	16	13	13	19	16	17	6	8	10	5	4	7	15	12	16
		1	1	0												
	1															
								3	3	2+	2+	2	0	1	1	2
		0	0	2												
+	2	2	2	2+	5+	6	5	2+	2	4	3	3	3+	2	2	1+
+	1+	2	2	2	1	1	1+	2	2	P	1	1	0	1	2	3
+	1	3	3	3+	4	2	6+	3	3	4	3	2+	3+	4+	4+	5+
	3+	4+	4+	6+	5+	9	7+	6	7	4+	3	2	4	2	1	3
	2	2	2	P	4	4	4+	0	P	1	2	2	P			
	2	2	2	3	3	3	1+	1+	1	1	1	1	1	2	2	3
	12	16	16	18	22	25	24	17	18	16	15	13	11	12	12	17
	0	0	0	P	2	2	2	0	P	1+	2	2	2			
	2	3	3	0				0	0	P	2	2	1	1	1	1
	2	3	3	1+	4	4	1+	3+	3	1+	3	3	3	1	1	1
	4	6	6	1	6	6	3	3	3	2	7	7	6	2	2	2
								P	0	0						
					0	0	P	1	1	1						
		0	P	0				P	0	0				0	0	1
		0	P	1+				1	1	1				1	1	0
		P	P	P	P	P	0	P	P	P	P	0	0			
	6	6	6	5	2+	2+	2	4	4	3	2	1+	2	2	2	6
	0	2	2	2	1	0	1	1+	1	1+	1	P	1+	1	1	3
		1	1	1				P	P	1	P	0	1	1	0	1
		0	0	1	2	2	2+	4	4	4	0	0	1	1	1	P
	6	9	9	10	5	4	5	11	11	11	3	1	5	6	5	11
	39	47	44	42	52	51	49	37	40	39	30	25	29	35	31	46

The Forest Service of the U.S. Department of Agriculture

. . . Conducts forest and range research at more than 75 locations from Puerto Rico to Alaska and Hawaii.

. . . Participates with all State forestry agencies in cooperative programs to protect and improve the Nation's 395 million acres of State, local, and private forest lands.

. . . Manages and protects the 187-million-acre National Forest System for sustained yield of its many products and services.

The Pacific Southwest Forest and Range Experiment Station

represents the research branch of the Forest Service in California and Hawaii.

Mannan, Deborah M. Finch, and Lawrence R. DeWeese.
1979. **Effects of Sevin-4-Oil, Dimilin, and Orthene on forest birds in Northeastern Oregon.** Res. Paper PSW-148, 19 p., illus. Pacific Southwest Forest and Range Exp. Stn., Forest Service, U.S. Dep. Agric., Berkeley, Calif.

A field study begun in 1975 was designed to assess the effects of three insecticides on nontarget nesting birds. Breeding bird density, species diversity, nesting success, brain cholinesterase activity, and presence of sick or dead birds were evaluated on control and treatment plots during the year of spraying and 1 year after. No adverse effects were detected in the Dimilin plots, and no major effects in the Sevin-4-Oil plots, although 2 of 55 birds showed brain cholinesterase depression. In the Orthene plots, however, studies of brain cholinesterase activity showed severe and prolonged depression (commonly 30 to 50 percent) for up to at least 33 days. Abnormal behavior symptomatic of organophosphate poisoning was also observed in the field, although the overall impact on the nesting bird population is not fully understood.

Retrieval Terms: Sevin-4-Oil (carbaryl); Orthene (acephate); Dimilin (diflubenzuron); forest birds; brain cholinesterase.

Richmond, Merle L., Charles J. Henny, Randy L. Floyd, R. William Mannan, Deborah M. Finch, and Lawrence R. DeWeese.
1979. **Effects of Sevin-4-Oil, Dimilin, and Orthene on forest birds in Northeastern Oregon.** Res. Paper PSW-148, 19 p., illus. Pacific Southwest Forest and Range Exp. Stn., Forest Service, U.S. Dep. Agric., Berkeley, Calif.

A field study begun in 1975 was designed to assess the effects of three insecticides on nontarget nesting birds. Breeding bird density, species diversity, nesting success, brain cholinesterase activity, and presence of sick or dead birds were evaluated on control and treatment plots during the year of spraying and 1 year after. No adverse effects were detected in the Dimilin plots, and no major effects in the Sevin-4-Oil plots, although 2 of 55 birds showed brain cholinesterase depression. In the Orthene plots, however, studies of brain cholinesterase activity showed severe and prolonged depression (commonly 30 to 50 percent) for up to at least 33 days. Abnormal behavior symptomatic of organophosphate poisoning was also observed in the field, although the overall impact on the nesting bird population is not fully understood.

Retrieval Terms: Sevin-4-Oil (carbaryl); Orthene (acephate); Dimilin (diflubenzuron); forest birds; brain cholinesterase.

Richmond, Merle L., Charles J. Henny, Randy L. Floyd, R. William Mannan, Deborah M. Finch, and Lawrence R. DeWeese.
1979. **Effects of Sevin-4-Oil, Dimilin, and Orthene on forest birds in Northeastern Oregon.** Res. Paper PSW-148, 19 p., illus. Pacific Southwest Forest and Range Exp. Stn., Forest Service, U.S. Dep. Agric., Berkeley, Calif.

A field study begun in 1975 was designed to assess the effects of three insecticides on nontarget nesting birds. Breeding bird density, species diversity, nesting success, brain cholinesterase activity, and presence of sick or dead birds were evaluated on control and treatment plots during the year of spraying and 1 year after. No adverse effects were detected in the Dimilin plots, and no major effects in the Sevin-4-Oil plots, although 2 of 55 birds showed brain cholinesterase depression. In the Orthene plots, however, studies of brain cholinesterase activity showed severe and prolonged depression (commonly 30 to 50 percent) for up to at least 33 days. Abnormal behavior symptomatic of organophosphate poisoning was also observed in the field, although the overall impact on the nesting bird population is not fully understood.

Retrieval Terms: Sevin-4-Oil (carbaryl); Orthene (acephate); Dimilin (diflubenzuron); forest birds; brain cholinesterase.

Richmond, Merle L., Charles J. Henny, Randy L. Floyd, R. William Mannan, Deborah M. Finch, and Lawrence R. DeWeese.
1979. **Effects of Sevin-4-Oil, Dimilin, and Orthene on forest birds in Northeastern Oregon.** Res. Paper PSW-148, 19 p., illus. Pacific Southwest Forest and Range Exp. Stn., Forest Service, U.S. Dep. Agric., Berkeley, Calif.

A field study begun in 1975 was designed to assess the effects of three insecticides on nontarget nesting birds. Breeding bird density, species diversity, nesting success, brain cholinesterase activity, and presence of sick or dead birds were evaluated on control and treatment plots during the year of spraying and 1 year after. No adverse effects were detected in the Dimilin plots, and no major effects in the Sevin-4-Oil plots, although 2 of 55 birds showed brain cholinesterase depression. In the Orthene plots, however, studies of brain cholinesterase activity showed severe and prolonged depression (commonly 30 to 50 percent) for up to at least 33 days. Abnormal behavior symptomatic of organophosphate poisoning was also observed in the field, although the overall impact on the nesting bird population is not fully understood.

Retrieval Terms: Sevin-4-Oil (carbaryl); Orthene (acephate); Dimilin (diflubenzuron); forest birds; brain cholinesterase.

d States
rtment of
ulture

t Service

c Southwest
t and Range
riment Station

arch Paper
-149

Roadless Area-Intensive Management Tradeoffs on the Sierra National Forest, California

SITY LIBRARY
FEB 11 1981

DOCUMENTS
DEPOSITORY ITEM
FEB 9 1981
CLEMSON
LIBRARY

Robert J. Hrubes Kent P. Connaughton Robert W. Sassaman

The Authors

ROBERT J. HRUBES is a research forest economist, Pacific Southwest Forest and Range Experiment Station, Berkeley, California. **KENT P. CONNAUGHTON** and **ROBERT W. SASSAMAN** are research forest economists, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon.

ACKNOWLEDGMENTS

We thank K. Norman Johnson, Utah State University, for developing the mathematical programing model used in this study and for preparing the data and making the computer runs. We are also indebted to Klaus Barber, Pacific Southwest Region, Forest Service, U.S. Department of Agriculture, and John Kruse, Sierra National Forest, for compiling and preparing data. Without their firsthand knowledge of the Sierra National Forest, the study would not have been possible.

Roadless Area-Intensive Management Tradeoffs on the Sierra National Forest, California

Robert J. Hrubes Kent P. Connaughton Robert W. Sassaman

CONTENTS

	Page
Introduction	1
The Test Forest	1
General Approach	2
Alternatives	2
Base Alternatives	2
No-Reallocation Alternative	3
Reallocation Alternative	3
Partial Reallocation Alternatives	3
Results	4
Effects on Timber Harvest	4
Effects on Financial Indices and Employment	5
Effects on Nontimber Benefits	8
Conclusions	10
Literature Cited	11
Appendix	11

Pacific Southwest Forest and Range Experiment Station
P.O. Box 245
Berkeley, California 94701

December 1979

IN BRIEF

Hrubes, Robert J., Kent P. Connaughton, and Robert W. Sassaman.
1979. **Roadless area-intensive management tradeoffs on the Sierra National Forest, California.** Res. Paper PSW-149, 11 p., Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

Retrieval Terms: wilderness areas, roadless areas, allocations, timber management, timber supply, alternatives, Sierra National Forest, simulation, statistical methods.

Because of increasing debate over the use of National Forest lands, a proposal has been made to help resolve the conflict between wilderness allocation and timber management by reallocating roadbuilding funds in roadless areas to investments in more intensive timber management on roaded lands. Roadless areas thus precluded from planned future development would be logical candidates for wilderness designation; the associated loss in timber harvests would be compensated by anticipated yields resulting from investments in more intensive timber management. The research described herein tested this tradeoff hypothesis on the Sierra National Forest of northern California.

The harvest levels for the reallocation alternatives are based upon specific assumptions. Thus, the calculated harvest levels reported should not be considered as what could now be obtained from the Sierra National Forest, but rather what might be reached if the stated assumptions are satisfied.

Results of this research indicate that programed timber harvest levels cannot be maintained when roadless areas are withdrawn and funds are reallocated. Approximately one half of the loss in programed harvest can be made up. Additional investments in intensive timber management fail to make up the entire harvest loss, partly because of other restrictions imposed in the harvest scheduling process. The nondeclining, even-flow constraint as well as environmental considerations, realized through various harvesting constraints, serve to limit the efficacy of additional investment funds. However, actual (versus programed) harvest effects would not be as significant, since the recent selling level in the Sierra National Forest has been below the programed harvest level.

Consistent with the harvest effects on the Sierra National Forest, revenues to the Forest Service, county payments, present net worth of the timber harvest plan, and regional timber-based employment decline when the roadless areas are withdrawn from the timber management base.

Major nontimber and environmental tradeoffs are also anticipated if this plan were implemented. Fish, wildlife, and visual resources would benefit in roadless areas. Game species would benefit in roaded areas. Conversely, adverse effects on fish, visual resources, and developed and dispersed recreation potential would occur in the roaded areas; game species and road-related dispersed recreation would be adversely affected in the roadless areas.

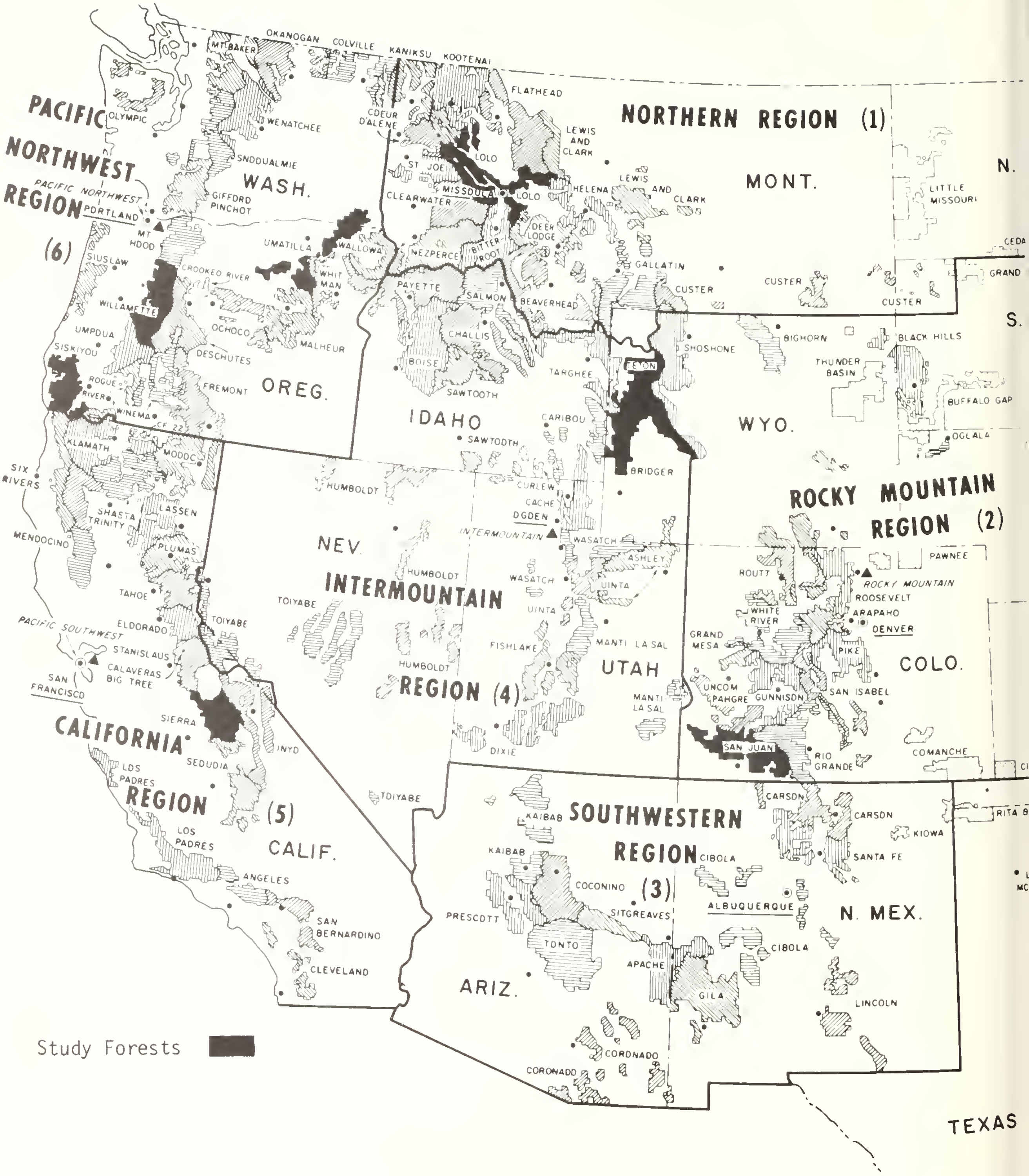


Figure 1—Seven western National Forests were selected for detailed study of their ability to maintain current harvest levels under roadless area removal and fund transfer.

Recent debate over the USDA Forest Service's Roadless Area Review and Evaluation (RARE II) and the resulting administration proposals for wilderness designation make obvious that no simple solution exists to the disposition of remaining roadless areas within the National Forest System. Heightened political sensitivity is due perhaps to the fear that significant costs will be incurred, regardless of the use allocation of these roadless areas, for either wilderness or commodity production. Because of these costs, wilderness use and commodity production on wildlands invariably are considered within the context of conflict.

A strategy to circumvent or at least to mitigate the severity of conflict would surely help to attain a politically acceptable land-use allocation of the remaining roadless areas. Such a strategy must aim at either lessening the allocation costs for resource development—cost in terms of destroying de facto wilderness—or offsetting the opportunity costs of wilderness allocation—resource flows foregone. The first option, reducing the wilderness costs of resource development, appears infeasible unless the term wilderness is drastically redefined. In the present context, the wilderness potential is essentially destroyed when land is developed for commodity production.

What, then, is the potential of the second option—offsetting opportunity costs of wilderness allocation? In 1977, Kutay[1] designed a strategy to negate the effects of wilderness allocation on timber harvest levels. He proposed that road construction funds that would have been used in the roadless areas be reallocated to intensive timber management funds for areas already roaded. The goal was to compensate for the loss of timber flows from roadless areas allocated to wilderness through intensified timber management on already roaded areas.

A study team comprised of USDA Forest Service economists and planning personnel was organized to test the feasibility and consequences of Kutay's proposal. The team selected seven western National Forests for detailed study, testing each for its ability to maintain current harvest levels under roadless area removal and fund transfer *(fig. 1)*. The test was made within the context of existing Forest Service policies and procedures; results were later published in a summary document (Fight and others 1978). This paper examines in more detail the procedures and results of that study as related to one of the seven test sites, the Sierra National Forest, in the Pacific Southwest Region.

THE TEST FOREST

Several criteria were used to select the test forest. First, timber data suitable for use in the timber harvest scheduling model used in the study had to be available. Second, a significant portion of its commercial forest land had to be in roadless area classification. Third, it was desirable that the road costs, land productivity, and multiple-use restrictions on the test forest be as representative of the regional average as possible. In the Pacific Southwest Region, the Sierra National Forest best met these criteria.

The Sierra National Forest lies on the west side of the Sierra Nevada, in California, between the crest and the foothills adjacent to the south side of Yosemite National Park. Mixed conifer is the major timber type. Other types include ponderosa pine, red fir, and subalpine types. Most of the productive forest land lies at elevations ranging from 4000 to 6000 feet. The Forest contains about 1.3 million acres of National Forest land, of which 28 percent was considered regulated commercial forest land for purposes of this study. The National Forest acreage in roadless areas for this study was about 352,000 acres, of which 14 percent was considered regulated commercial forest land. The average volume of chargeable harvest[2] for the past decade was about 20 million cubic feet per year.

---

[1] Kutay, Kurt. April 1977. Oregon economic impact assessment of proposed wilderness legislation. Unpublished. On file Pacific Northwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Portland, Oreg.

[2] Chargeable harvest is that portion of the annual harvest volume credited to the programed harvest. Examples of nonchargeable harvests are those harvests from the unregulated component.

GENERAL APPROACH

The general approach for testing the feasibility of the tradeoff strategy involved simulating timber harvest schedules under alternative land base and funding level assumptions. For each alternative, both programed harvest and potential yield for timber were calculated.[3] Timber harvest schedules were formulated with a linear programing model, Model II, developed by K. Norman Johnson.[4] As with actual harvest schedules developed in the Sierra National Forest planning process, Model II was programed to maximize the first decade harvest level subject to a nondeclining evenflow constraint. That is, harvests are allowed to rise over time, but not fall.

In terms of relevance to the hypothesis, an important phase of the harvest scheduling procedure is establishing additional programing constraints that reflect or are induced by environmental considerations. Land management planners have found that in the absence of these environmentally induced constraints, optimization models such as Model II tend to schedule concentrated harvests within a small geographic area over a relatively short time period. Obviously, such concentrated harvesting activity could result in unacceptably high environmental costs. Thus, planners have found it necessary to impose additional constraints in the scheduling process in order to limit the degree of spatial concentration of harvesting activities. For the Sierra National Forest scheduling runs, restrictions were imposed on the maximum allowable clearcut acres per decade, in the standard and marginal components separately. In addition, restrictions were imposed on the number of regeneration harvest acres by standard and marginal components.

Environmental considerations are also reflected implicitly in preparing input for the mathematical harvest scheduling model. The definition of management alternatives and working-group land-class condition-class combinations can implicitly reflect environmental considerations (see the user's manual referenced in footnote 4 for a discussion of these concepts). The management alternatives and class combinations, in part, form the structure of the mathematical representation of the "real world." As such, their definitions can influence the optimal schedule.

For comparison, a base alternative was developed, the intention of which was to simulate the actual timber harvest schedule for the test forest under current management directions. To directly address the feasibility of the tradeoff strategy, a reallocation alternative was constructed, entailing the removal of roadless areas from the timber management land base and transferring subsequent savings in road construction costs to investments in more intensive timber management. Additional alternatives were also constructed that involved roadless area removals without budget reallocation and 50 percent roadless area removal *(table 1).*

ALTERNATIVES

Base Alternative

The base alternative incorporated current forest plans for timber management, road construction, multiple-use constraints, and funding levels. Under the base alternative, the existing roadless areas are programed for eventual road construction and timber harvesting. Forest engineers estimated that 196 miles of road construction would be required to carry out the base alternative in roadless areas. The base alternative included the standard, special, and marginal components of the regulated forest base amounting to 357,000 acres. Management of these acres consisted of stocking the nonstocked (cut-over) backlog, reforestation, stocking level control, thinning, and final harvests. The final harvest was programed under clearcut, shelterwood, and selection silvicultural systems, as appropriate, to meet silvicultural and multiple-use objectives of the forest.

The definition of intensive timber management activities is central to the study, since these activities directly determine the feasibility of the tradeoff strategy. A wide spectrum of management actions fall within the limits of intensive timber management—the

---

[3] Potential yield is a ceiling on the volume of timber that may be sold from a forest for the next 10 years. The programed harvest for a forest is the part of the potential yield that is scheduled for sale during a specific year.

[4] Johnson, K. Norman, and Daniel D. Jones. 1979. Timber Harvest Scheduling Model—User's Guide and Operations Manual. Unpublished. On file Forest Serv., U.S. Dep. Agric., Timber Management Staff, Fort Collins, Colo.

Table 1—*Summary of alternatives*

Alternative	Roadless areas available for timber management	Funds reallocated to more intensive timber management
1. Base	All	No
2. 50 percent out	Half	No
3. 50 percent out—reallocation	Half	Yes
4. 100 percent out	None	No
5. 100 percent out—reallocation	None	Yes

planting of genetically improved growing stock, irrigation, fertilization, repetitive artificial regeneration, and intensive stand grooming to name a few. While many management techniques are used to improve the quantity and quality of yields, quantifiable effects of most intensive management activities are not available because of the required observation time.

Long range mathematical modeling nevertheless requires quantified estimates. This study uses a conservative approach, assuming the net effect of intensive management on a stand to be a one-decade acceleration in the time required to attain a stocking level sufficient to allow commercial thinning. The intensive management activities used to bring about this acceleration are assumed to be the planting of genetically improved growing stock and a greater use of precommercial thinning and release. Intensive timber management practices such as fertilization and irrigation were not considered because quantifiable results of those practices would require even greater assumptions.

No-Reallocation Alternative

The no-reallocation alternative consisted simply of removing all roadless areas from the timber harvest land base without compensatory additions to the budget on the remaining land area. The alternative measures the timber supply effects of simply allocating all roadless areas within the forest to wilderness or any other exclusionary classification. The difference in 10-year harvests between the no-reallocation alternative and the base alternative serves as a reasonable measure of the harvest consequences of noncompensatory wilderness allocation.

Reallocation Alternative

Comparing the reallocation alternative and base alternative harvest schedules determines the extent to which the tradeoff strategy can offset the timber opportunity cost of wilderness allocation. The reallocation alternative differs from the alternative in only one area: the budget for intensive timber management in the reallocation alternative was increased by the amount of money that would have been spent roading the roadless areas on a decade-by-decade basis. The increased budget results in the availability of genetically improved growing stocks, as discussed above.

The amount of money available was determined by estimating costs for road construction, reconstruction, and maintenance necessary to fully develop the roadless areas. The amount to be reallocated was equal to the costs avoided by not developing roadless areas, less any increased roading costs incurred in the currently accessible areas as a result of not developing the roadless areas. No increased costs were projected.

The cost saving consisted of two components: 1) purchaser credits generated from timber sale receipts in the roadless areas and 2) appropriated funds. If roadless areas are not developed, purchaser credits are not generated; therefore, this saving then is not available money. This fact does not influence the study results, but it does mean that reallocation alternatives could be implemented only if Congress appropriated additional money for intensive management.

Partial Allocation Alternatives

Timber harvest schedules were also designated for a withdrawal of 50 percent of the roadless areas. To the extent that a wilderness allocation of all roadless areas in a National Forest may not be politically feasible, the partial allocation alternatives should be of interest to forest planners. The partial allocation alternatives also support the observation that no linear relationship exists between the size of roadless area withdrawal and the magnitude of timber harvest loss.

Selecting half of the roadless area for removal was based on:

- Quality of the area for wilderness
- Public concern for the area as wilderness
- Congressional and administrative interest
- Manageability
- Direct costs and opportunity costs of permanent roadless designation

The intention was to identify that half of the roadless area in the forest that would be the most likely candidate for wilderness allocation, in the judgment of Forest Service planners.

RESULTS

Effects on Timber Harvest

The harvest levels for the reallocation alternatives reported *(fig. 2)* are based partly on two specific assumptions. Therefore, the harvest levels should not be considered as what could now be obtained from the Sierra National Forest, but rather what might be reached if these two assumptions are satisfied.

One assumption is that funds saved by not roading certain areas would be spent on planting genetically improved growing stock. At present—and possibly for the next decade or more—planting such stock is not a viable widescale practice in California. Another assumption is that there would be "100 percent efficiency" in terms of actual harvest levels being equal to calculated programed harvest levels for both the standard and marginal components; that is, the calculated programed harvest levels will actually be attained. Although 100-percent efficiency may be a desirable goal in the long run, actual efficiency levels, according to the Sierra National Forest, have been 89 percent for the standard component and 30 percent for the marginal component. The *appendix* illustrates the estimated harvest levels based on the actual efficiency levels and the absence of the two specific assumptions.

We emphasize that the results reported *(fig. 2)* are not obtainable under current conditions. But by removing the two specific assumptions from the analysis—especially the second one—there would no longer be any tradeoff strategy to be examined.

Two major conclusions on harvest impact are apparent, nevertheless, from the alternative levels *(fig. 2)*. First, it is not possible to maintain the programed harvest on the Sierra National Forest if roadless areas are withdrawn and funds are reallocated. Only about one half of the loss can be made up through more intensified management. Second, the recent selling level of the Sierra National Forest has been considerably below the programed harvest level. As such, the results of this study indicate that it may be possible to maintain the recent selling level under a strategy of roadless area withdrawal and fund reallocation.

However, an important warning about the general conclusions bears mentioning. The inability to make up the loss resulting from roadless area withdrawal may be a valid conclusion only within the context of the constraints presently imposed on the Sierra National Forest timber harvest scheduling process. The most important constraints are nondeclining, even-flow, environmentally induced restrictions and available intensive management silvicultural practices.

The Model II scheduling runs reveal that several of the environmentally induced maximum clearcut and regeneration harvest restrictions were indeed binding; that is, these restrictions did limit the harvest level, explaining in part the inability to maintain the "pre-roadless area removal" programed harvest level through the allocation of more investment funds. The nondeclining yield constraint was also binding. The effect of a narrowly defined spectrum of available intensive management opportunities cannot be deduced from the Model II runs.

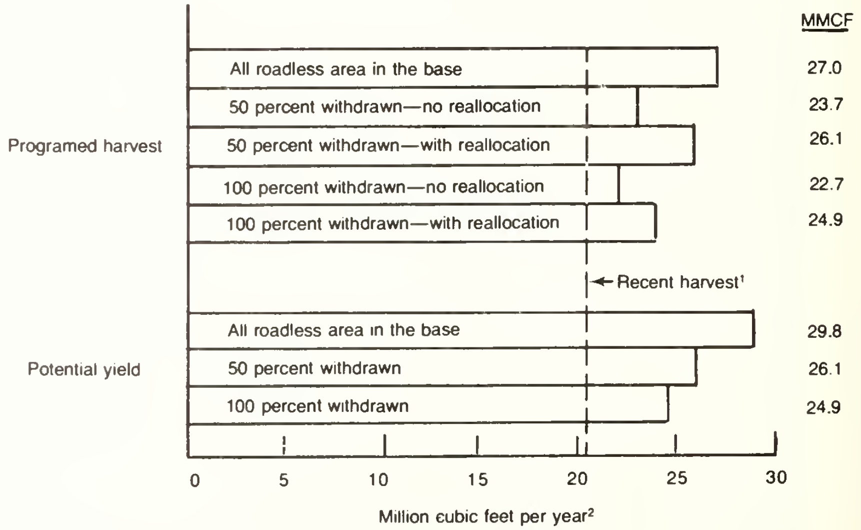


Figure 2—Alternative harvest levels, Sierra National Forest

[1] The recent harvest is less than the base programed harvest primarily because of inadequate financing of the timber sale program.

[2] Harvests can be converted to board feet, local scale, by using the board-foot/cubic-foot ratio 6:3.

Effects on Financial Indices and Employment

The purpose of the financial analysis is to determine the effect of some broad roadless-area allocation alternatives on gross revenues, road costs, silvicultural costs, net revenues, in-lieu-of-tax payments to counties, present net worth, and employment. The county payments and employment results are valuable indicators of the effect of the Sierra National Forest harvest changes on local economies. The present net worth calculations are important components of a national efficiency analysis. Finally, the revenue and cost results are useful indicators of the effect of the alternatives on Forest Service budgets and receipts to the Treasury.

We have no financial results for individual roadless areas. We know, however, that within the broad roadless area aggregates analyzed in this study, individual roadless areas vary tremendously in timber inventory, commercial forest land, productivity, and financial values.

Silvicultural and timber sale preparation and administration costs were supplied by Sierra National Forest personnel *(table 2)*. The higher level of intensive management made possible by reallocation is shown by the increased costs of precommercial thinning, release, and reforestation for the reallocation alternatives. The costs in *table 2* do not include charges for general administration or overhead costs of program administration.

Table 2—*Silvicultural and timber sale preparation and administration costs for the Sierra National Forest*[1]

Cost category and working group	Dollars per acre	
	Base alternative	Reallocation alternative
Precommercial thinning, all timber types	63.50	[2]76.80
Release, all timber types	25.90	[3]31.08
Timber sale preparation and administration, all timber types	[4]27.20	[4]27.20
Reforestation, mixed conifer	135.80	162.96
Reforestation, ponderosa pine	194.00	232.80
Reforestation, red fir	164.30	197.16
Reforestation, subalpine fir	135.80	135.80

[1] Costs include contract preparation, contract costs, materials and labor and contract administration. Costs do not include general administration and program management charges.

[2] Cost for subalpine fir working group reallocation alternatives is $63.50 per acre.

[3] Cost for subalpine fir working group reallocation alteraatives is $25.90 per acre.

[4] Dollars per MBF.

Road construction and road cost data were also provided by Sierra National Forest personnel:

Total miles to be constructed in roadless areas	196 miles
Total construction costs	$21,400,000
Cost per mile	$109,000
Construction, by decade	
First	60 percent
Second	25 percent
Third	10 percent
Fourth	5 percent
Roadless miles per section in roadless areas	
Regulated CFL acres	2.5 miles/section
Total National Forest acres	0.4 mile/section
Reconstruction cost per mile	$25,000
Reconstruction cycle	60 years
Maintenance costs per mile per year	$450

The road construction mileage and costs would be necessary to support the base programed harvest. Reconstruction and maintenance costs were also included in the financial calculations.

Two assumptions about future costs were used in the analysis. First, future real costs for all cost items would remain constant at the levels specified by the Sierra National Forest. Second, costs for labor intensive practices (reforestation, precommercial thinning, and timber sale preparation, and administration) would increase to the year 2020 at the same rate as real per capita income in California (U.S. Water Resources Council 1974). Other cost items were assumed constant. After 2020, costs for labor intensive practices are assumed constant at their 2020 levels.

Stumpage prices for each working group in the standard component are shown in *table 3*. Prices for the marginal component were estimated to be $35 per one thousand board feet lower than the prices for the corresponding working group in the standard component. Quality differences and logging and hauling cost differences account for the lower prices on the marginal component. All stumpage prices are high bid, or the price which one would observe if the road system were in place.

Table 3—*High bid stumpage prices for 1977, by working group and land class, Sierra National Forest*

Working group	Land class: Standard	Land class: Marginal
	Dollars	
Mixed conifer	99.81	64.81
Ponderosa pine	121.49	86.49
Red fir	36.11	1.11
Subalpine	15.87	—

Three assumptions were made about future stumpage prices: 1) prices would remain constant at the current level reported for the Sierra National Forest; 2) prices would follow trends projected by an early version of the Timber Assessment Softwood Market Model,[5] assuming that Forest Service harvest levels in the Pacific Southwest Region would not be affected by roadless area withdrawals; and 3) prices would follow trends projected by the Timber Assessment Softwood Market Model, assuming that Forest Service harvest levels in the Pacific Southwest Region would be affected by roadless area withdrawals in the same proportion as the harvest change for each alternative on the Sierra National Forest. Prices for the latter two projections increased at an average annual compound growth rate of 2.1 percent to the year 2020, and were constant thereafter.

Effects on employment were estimated with an input-output model recently developed for the Sierra National Forest and the immediately surrounding area.[6] For this 12-sector model, industry gross output figures were established through direct survey. Interindustry transaction figures were based on national breakdowns and available survey information.

Harvest level changes were assumed to translate directly and fully into changes in sectoral sales to final demand. Private sector harvest levels were assumed not to be influenced by Sierra National Forest harvests. Employment effects can be interpreted as deviations from the direct, indirect, and induced employment levels associated with the base programed harvest. But since the recent selling level has been less than the programed harvest, these employment deviations represent, in part, losses in employment potential and not actual job losses.

Increases in dispersed, nonmotorized, recreation-related employment were not considered in the analysis. It was considered unlikely that the establishment of additional wilderness areas in the Sierra National Forest would have significant impact on that type of employment. Also, no attempt was made to estimate the employment effects of changes in payments to counties.

Revenues, county payments, and employment decline as the roadless areas are withdrawn *(table 4)*.

Table 4—*Four-decade average financial effects and employment effects of withdrawing roadless areas and reallocating funds to intensive management, Sierra National Forest*[1]

Item	Base programed harvest	Change from base when 50 percent roadless withdrawn	Change from base when 100 percent roadless withdrawn
Harvest (MMCF/yr)	27.0	−0.9	−2.1
Gross revenue ($1,000,000/yr)	34.2	−1.2	−1.9
Cost of roads ($1,000,000/yr)	—[2]	−0.3	−0.7
Cost of cultural treatments ($1,000,000/yr)	—[2]	−0.1	+0.2
Cost of selling timber ($1,000,000/yr)	—[2]	−0.1	−0.1
Net revenue (Item 2−Items 3, 4, and 5) ($1,000,000/yr)	—[2]	−0.7	−1.4
Payments to counties ($1,000,000/yr)	8.5	−0.3	−0.5
Present net worth for 10 decades at 5 percent ($1,000,000)	—[2]	−0.7	−13.2
Present net worth for 10 decades at 10 percent ($1,000,000)	—[2]	+3.0	0.0
First decade's average annual total employment (person-years)	2,438	−81	−203

[1] Trends in real costs and real stumpage prices with no harvest changes due to roadless area withdrawals on other Region 5 National Forests were used. Because the recent harvest on the Sierra National Forest is less than the programed harvest with all of the roadless area withdrawn, all reductions in revenues and employment represent losses in opportunities for increases rather than reductions from actual recent levels.

[2] Not available.

---

[5] Adams, Darius M., and Richard W. Haynes. 1978. A preliminary description of the 1980 Timber Assessment Softwood Market Model. Unpublished report. On file Pacific Northwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Portland, Oreg.

[6] Canavan, James J. 1978. Input-output analysis for land management planning. Unpublished report. On file Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

Cultural treatment costs, which are higher on a per-acre basis for the reallocation alternatives, increase as all of the roadless areas are withdrawn and decrease if only one half of the roadless areas are withdrawn. Present net worth (PNW) is sensitive to the interest rate. PNW declines if all or one half of the roadless areas are withdrawn and calculations are made with a 5 percent interest rate. PNW increases when one half of the roadless areas are withdrawn and is unchanged when all of the roadless areas are withdrawn and calculations are made with a 10 percent interest rate. The results shown in *table 4* pertain to the assumptions of increasing costs and increasing prices, with prices on the Sierra National Forest assumed to be unaffected by roadless area withdrawals elsewhere in Pacific Southwest Region.

When other cost and price assumptions are used, the results are similar to those reported above, with the exception of present net worth and net revenue. Present net worth increases for both reallocation alternatives and both interest rates when the results are calculated with constant costs and constant revenues *(table 5)*. Increases in net revenue and large increases in present net worth (with both interest rates) are realized when calculations are made with increasing costs and increasing prices that reflect the price effects of proportional harvest changes on other National Forests in the Pacific Southwest Region *(table 6)*.

Table 5—*Four-decade average financial effects and employment effects of withdrawing roadless areas and reallocating funds to intensive management, Sierra National Forest*[1]

Item	Base programed harvest	Change from base when 50 percent roadless withdrawn	Change from base when 100 percent roadless withdrawn
Harvest (MMCF/yr)	27.0	−0.9	−2.1
Gross revenue ($1,000,000/yr)	15.0	−0.4	−0.8
Cost of roads ($1,000,000/yr)	—[2]	−0.3	−0.7
Cost of cultural treatments ($1,000,000/yr)	—[2]	0.0	−0.1
Cost of selling timber ($1,000,000/yr)	—[2]	0.0	−0.1
Net revenue (Item 2 – Items 3, 4, and 5) ($1,000,000/yr)	—[2]	−0.1	−0.2
Payments to counties ($1,000,000/yr)	3.7	−0.1	−0.2
Present net worth for 10 decades at 5 percent ($1,000,000)	—[2]	+5.8	+4.1
Present net worth for 10 decades at 10 percent ($1,000,000)	—[2]	+2.9	+0.2

[1] Constant real prices and constant real costs were used.

[2] Not available.

Table 6—*Four-decade average financial effects and employment effects of withdrawing roadless areas and reallocating funds to intensive management, Sierra National Forest*[1]

Item	Base programed harvest	Change from base when 50 percent roadless withdrawn	Change from base when 100 percent roadless withdrawn
Harvest (MMCF/yr)	27.0	−0.9	−2.1
Gross revenue ($1,000,000/yr)	34.2	−0.4	0.0
Cost of roads ($1,000,000/yr)	—[2]	−0.3	−0.7
Cost of cultural treatments ($1,000,000/yr)	—[2]	−0.1	+0.2
Cost of selling timber ($1,000,000/yr)	—[2]	0.0	−0.1
Net revenue (Items 2, 3, 4, and 5) ($1,000,000/yr)	—[2]	+0.1	+0.5
Payments to counties ($1,000,000/yr)	8.5	−0.1	0.0
Present net worth for 10 decades at 5 percent ($1,000,000)	—[2]	+13.6	+20.1
Present net worth for 10 decades at 10 percent ($1,000,000)	—[2]	+9.3	+14.5

[1] Trends in real costs and real prices with proportional harvest changes on other Region 5 National Forests were used.

[2] Not available.

Several factors explain the behavior of present net worth and net revenue. First, there is considerable decade-to-decade variation in gross revenue within and between alternatives which is not due to price increases over time or total harvest changes. Even though the harvest level for each alternative is constant for 10 decades, there is a different mix of working groups, each with its own price, which contributes to the decadal harvests. For example, the first decade harvests for the reallocation alternatives are more heavily concentrated than the base alternative in the high value mixed conifer working group.

The result is that the first decade gross revenues for the reallocation alternatives are higher than the base gross revenue, even though the opposite is true for most ensuing decades. Since present net worth calculations, particularly those with the 10 percent interest rate, weigh first-decade revenues and costs most heavily, present net worth behaves differently than four-decade-average net revenue. Second, the road cost savings of reallocation alternatives are concentrated in the early decades, particularly the first. Present net worth calculations are influenced most significantly by these cost savings because they occur close to the present. Finally, when proportional harvest changes on other National Forests are considered, the price increases due to contraction of harvest elsewhere in the Region are sufficient to curtail drastically the declines in four-decade-average gross revenue. The higher prices even lead to large increases in present net worth. Note that these changes in present net worth are dominated by assumed changes in the rest of the Pacific Southwest Region and are not indicative of land allocation alternatives on the Sierra National Forest alone.

The financial results do not include a complete accounting of all benefits and costs of harvest alternatives. For example, nontimber benefits, such as increased opportunities for wilderness recreation, and nontimber opportunity costs, such as decreased opportunities for developed and roadside recreation, are not included in the financial analysis because defensible estimates of their monetary values are not presently available. Changes in direct management costs of producing nontimber benefits and differences in forest protection costs are also not accounted for. Therefore, financial results must be interpreted with care and considerable attention must be directed to a subjective valuation of the nontimber consequences before one can draw firm conclusions about the economic desirability of a particular alternative.

The financial analysis quantifies the major changes in timber program benefits and costs. The results are useful measures of the impacts of alternatives on local community employment, payments to counties, receipts to the Federal Treasury, and Forest Service timber management budgets under alternative assumptions about the future course of prices and costs. The results are a necessary component of an efficiency analysis; though, as the above discussion suggests, firm conclusions about the efficiency implications of alternatives requires concurrent scrutiny of nontimber consequences.

Effects on Nontimber Benefits

Many kinds of tradeoffs are related to the withdrawal of roadless areas from the timber base and reallocation of road funds to intensified timber management on the remaining areas. To demonstrate this point, our analysis dealt with a comparison of the alternative Roadless Area Out—Reallocation (of road construction funds) with the base alternative.

Impacts were estimated with the threshold of concern (TOC) concept (Sassaman 1977) for five decades into the future for each nontimber benefit criterion. Major, minor, and neutral impacts were recognized according to their timing (decades one, two through four, and five+), nature (adverse or beneficial), and, in the case of major adverse impacts, the costs of mitigation.

Major impacts were identified as those exceeding the TOC, which is defined as the amount of impact that would generate one or more of the following effects: (1) create a public expression of concern or interest, (2) change long-term traditional use patterns, (3) require funds substantially in excess of usual planning budget levels to lower impacts to an acceptable level. Though undesirable, major adverse impacts are considered acceptable (within limits) under current interpretation of multiple-use objectives.

Impact estimates were obtained from resource specialists representing various disciplines. Schedules for road construction, intermediate and regeneration harvests, and management activities were provided. Specialists evaluated differences in these data between the base alternative and the reallocation alternative in terms of nontimber benefits and ecosystem criteria. Data for roadless areas and roaded areas were evaluated separately.

Since 1972, all RARE I and II roadless areas—except those included in a completed land use plan—have been closed to timber harvesting, even though they are part of the commercial forest land base. Road construction and timber harvesting have been concentrated outside the roadless areas. As a result, adverse environmental impacts are beginning to develop and are in danger of exceeding acceptable levels on many National Forests. Both beneficial and adverse impacts are expected when transferring from the present condition to the base programed harvest; however, our concern is limited to changes expected between the base programed harvest and the reallocation alternative.

Environmental Evaluation Criteria

To identify the physical/environmental impacts of the reallocation alternative vis-a-vis the base alternative, the associated timber harvest schedules were evaluated with regard to the following criteria:

- Water quality: Slope failure associated with timber harvests and roadbuilding activities (road sites, design, construction methods, and maintenance levels) are critical factors affecting quality of managed forest watersheds. Sediment introduced to forest streams largely determines the effect on water quality.
- Water quantity and timing of flow: Effects related to peak flow are more important than total water quality in areas with abundant water. Water quantity would be a significant concern on forest land adjacent to semiarid areas.
- Soil stability: Road construction, timber harvest operations, steepness of terrain, and soil characteristics all affect soil stability. Major problems may result from erosion and mass soil movement, threatening life and property.
- Soil productivity: Soil compaction, affected by frequency of timber harvest and type of machinery used, can be minimized by careful selection of harvesting systems. Similarly, proper handling of forest residues decreases nutrient loss.
- Forage production: On western National Forests, domestic forage production is usually associated with forested ranges utilized during the summer grazing season. Accessibility of the terrain to domestic livestock and the proximity of existing grazing allotments determine the amount of forage grazed.
- Resident cold water fish populations: Water quality and sport fishing pressure directly affect fish populations and associated habitats.
- Wildlife populations: Road construction and timber harvests alter the numbers, size, age, arrangement, and species composition of timber stands, thereby affecting wildlife habitats and associated wildlife populations.
- Opportunities for developed recreation: Developed recreation usually involves a relatively high density form of recreation centered around a developed site, such as a campground or boat launch. Frequently, the developed facilities (whether primitive or elaborate) are located at or near natural land features, such as lakes, streams, waterfalls, or scenic vistas that provide an attractive setting.
- Opportunities for road-related dispersed recreation: Opportunities for dispersed recreation related to roads include scattered activities usually not associated with developed areas, such as camping in a camper or trailer at a trail head, undeveloped stream, or lake site.
- Opportunities for dispersed off-road recreation: Opportunities for this type of recreation include backpacking, horseback riding, and certain types of off-road vehicles, and involve a more primitive form of camping not normally associated with developed or road-related dispersed recreation.
- Visual resources: An inverse relationship generally exists between visual resources (opportunities for viewing natural-appearing forest landscapes from a distance) and the total acreage disturbed at any time. Short term, adverse timber harvest affects may be minimized by proper shaping of the harvest unit to the natural characteristics of the land.
- Air quality: Burning slash produces air pollutants that directly affect air quality on a short-term, seasonal basis. Smoke management plans to overcome this problem include increased utilization and conversion of overmature forests to younger, less defective stands, thus reducing the need for burning slash.
- Mineral and energy development opportunities: Efficient development of mineral and energy resources are directly related to road accessibility.

Findings on Environmental Impacts

If the reallocation alternative were adopted in place of the base alternative on the Sierra National Forest, timber harvests would continue to be concentrated in roaded areas. Roadbuilding or road-related timber harvests would not occur in roadless areas. Given this assumption, there are anticipated to be seven major adverse and four major beneficial nontimber or environmental effects *(table 7)*. Five effects would involve roadless areas; six would involve roaded areas. Another 15 minor and 4 neutral effects are anticipated.

Major benefits involve fish and wildlife populations and visual resources. Fish and wildlife benefit by preserving their habitats in roadless areas. Visual resources benefit when landscapes remain undisturbed in the roadless areas.

The major adverse effects involve fish, wildlife, recreation, and visual resources. Fish habitats would be degraded in roaded areas. Conversely, an adverse impact on wildlife game species is expected in the roadless areas from opportunities forgone to increase browse in the roadless areas when they remain unroaded.

All three recreation criteria listed have major adverse impacts associated with them *(table 7)*. Those affecting developed recreation relate to the roaded areas. Those affecting dispersed recreation opportunities associated with roads relate to both roaded and roadless areas. In roaded areas, these effects are associated with increased timber harvest-related traffic and noise. In roadless areas, the effects relate to opportunities forgone to pursue road-related dispersed recreation.

Adverse effects on dispersed recreation opportunities away from roads would occur in the roaded areas of the Sierra National Forest as a result of decreased acreage in the roaded areas that are compatible to this type of dispersed recreation.

The last major adverse effect involves visual resources in the road areas that are more intensively managed to promote timber production. The visual resources may be adversely affected as the total area of naturally appearing forest landscapes declines.

Table 7—*Estimated effects of withdrawing roadless areas and intensifying timber management on remaining land in the Sierra National Forest*[1]

Resource	Assessment of Effects				
	Beneficial		Neutral	Adverse	
	Major	Minor	No change from base	Minor	Major[2]
Water quality		R		A	
Water quantity		A	R		
Water flow		A	R		
Soil stability		R		A	
Soil productivity		R		A	
Forage production (domestic)		A		R	
Fish populations (residential)	R				A
Wildlife populations (game species)	A				R
Wildlife populations (threatened and endangered species)	R	A			
Recreation opportunities (developed)				R	A
Opportunities for dispersed recreation related to roads					AR
Opportunities for dispersed recreation away from roads		R			A
Visual resources	R				A
Air quality		R	A		
Mineral and energy development			A	R	

[1] R = Roadless areas, A = "Accessible" areas.

[2] Major adverse effects, while undesirable, are within limits considered acceptable under current interpretation of multiple use objectives.

CONCLUSIONS

This study set out to answer the question: Can the programed harvest level on the Sierra National Forest be maintained when roadless areas are removed from future harvests and road construction funds are reallocated to intensive timber management? The results show that—given the study assumptions—the answer is no. Spending more money in timber management is not a viable option for maintaining programed harvest levels in the face of a declining land base. Why is this strategy, so commonly assumed to be viable, insufficient? Study results indicate that factors other than available investment funds also serve to limit the programed harvest level on the Sierra National Forest. Scheduling restrictions such as clearcut dispersion requirements and nondeclining even-flow may play a greater role in shaping programed harvest levels than the money available for investment in timber management. In general, these scheduling restrictions are induced from environmental and/or multiple-use considerations.

The study also found that while programed harvest levels cannot be maintained, it is possible to maintain the current actual harvest level on the Sierra National Forest. The implication of this finding is that the effect of the land withdrawal and investment reallocation is best described as a loss in the *capacity* of the Sierra National Forest to offer timber on the market within the limits imposed by environmental and multiple-use considerations.

LITERATURE CITED

Fight, Roger D., Kent P. Connaughton, Norman Johnson, and Robert W. Sassaman.
1978. **Roadless area intensive management tradeoffs on western national forests.** Western resource policy economics research. USDA Forest Service.

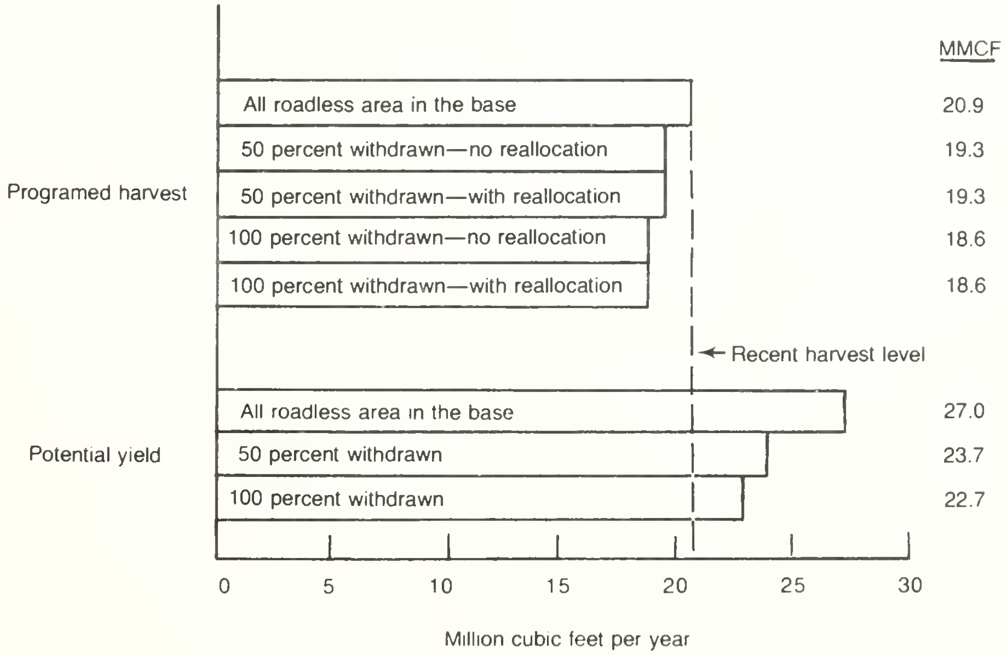
Sassaman, Robert W., and Robert M. Randall.
1977. **A method of evaluating impacts of timber harvests on nontimber forest resources**. Transactions of the 42nd American Wildlife and Natural Resources Conference. Wildlife Management Institute. Washington D.C.

U.S. Department of Agriculture.
1976. **Timber harvest scheduling issues study**. 292 p., For. Serv., U.S. Dep. Agric., Washington, D.C.

U.S. Water Resources Council.
1974. **OBERS projections. Volume 4: States.** Washington, D.C.

APPENDIX

Harvest levels when genetically improved growing stock is not assumed to be available and efficiency levels are 89 percent for the standard component and 30 percent for the marginal component (million ft^3/yr):



The Forest Service of the U.S. Department of Agriculture

. . . Conducts forest and range research at more than 75 locations from Puerto Rico to Alaska and Hawaii.

. . . Participates with all State forestry agencies in cooperative programs to protect and improve the Nation's 395 million acres of State, local, and private forest lands.

. . . Manages and protects the 187-million-acre National Forest System for sustained yield of its many products and services.

The Pacific Southwest Forest and Range Experiment Station

represents the research branch of the Forest Service in California and Hawaii.

Hrubes, Robert J., Kent P. Connaughton, and Robert W. Sassaman.
1979. **Roadless area-intensive management tradeoffs on the Sierra National Forest, California.** Res. Paper PSW-149, 11 p. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

This hypothesis was tested by a linear programing model: Roadless areas on the Sierra National Forest precluded from planned future development would be candidates for wilderness designation, and the associated loss in present and future timber harvests could be offset by investing in more intensive management. The results of this simulation test suggest that levels of programed harvesting cannot be maintained when roadless areas are withdrawn and funds are reallocated for intensive management on other areas. Additional tradeoffs were found in estimating the effects on fish, wildlife, recreation, and visual resources.

Retrieval Terms: wilderness areas, roadless areas, allocations, timber management, timber supply, alternatives, Sierra National Forest, simulation, statistical methods.

Hrubes, Robert J., Kent P. Connaughton, and Robert W. Sassaman.
1979. **Roadless area-intensive management tradeoffs on the Sierra National Forest, California.** Res. Paper PSW-149, 11 p. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

This hypothesis was tested by a linear programing model: Roadless areas on the Sierra National Forest precluded from planned future development would be candidates for wilderness designation, and the associated loss in present and future timber harvests could be offset by investing in more intensive management. The results of this simulation test suggest that levels of programed harvesting cannot be maintained when roadless areas are withdrawn and funds are reallocated for intensive management on other areas. Additional tradeoffs were found in estimating the effects on fish, wildlife, recreation, and visual resources.

Retrieval Terms: wilderness areas, roadless areas, allocations, timber management, timber supply, alternatives, Sierra National Forest, simulation, statistical methods.

Hrubes, Robert J., Kent P. Connaughton, and Robert W. Sassaman.
1979. **Roadless area-intensive management tradeoffs on the Sierra National Forest, California.** Res. Paper PSW-149, 11 p. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

This hypothesis was tested by a linear programing model: Roadless areas on the Sierra National Forest precluded from planned future development would be candidates for wilderness designation, and the associated loss in present and future timber harvests could be offset by investing in more intensive management. The results of this simulation test suggest that levels of programed harvesting cannot be maintained when roadless areas are withdrawn and funds are reallocated for intensive management on other areas. Additional tradeoffs were found in estimating the effects on fish, wildlife, recreation, and visual resources.

Retrieval Terms: wilderness areas, roadless areas, allocations, timber management, timber supply, alternatives, Sierra National Forest, simulation, statistical methods.

Hrubes, Robert J., Kent P. Connaughton, and Robert W. Sassaman.
1979. **Roadless area-intensive management tradeoffs on the Sierra National Forest, California.** Res. Paper PSW-149, 11 p. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

This hypothesis was tested by a linear programing model: Roadless areas on the Sierra National Forest precluded from planned future development would be candidates for wilderness designation, and the associated loss in present and future timber harvests could be offset by investing in more intensive management. The results of this simulation test suggest that levels of programed harvesting cannot be maintained when roadless areas are withdrawn and funds are reallocated for intensive management on other areas. Additional tradeoffs were found in estimating the effects on fish, wildlife, recreation, and visual resources.

Retrieval Terms: wilderness areas, roadless areas, allocations, timber management, timber supply, alternatives, Sierra National Forest, simulation, statistical methods.

United States
Department of
Agriculture

Forest Service

**Pacific Southwest
Forest and Range
Experiment Station**

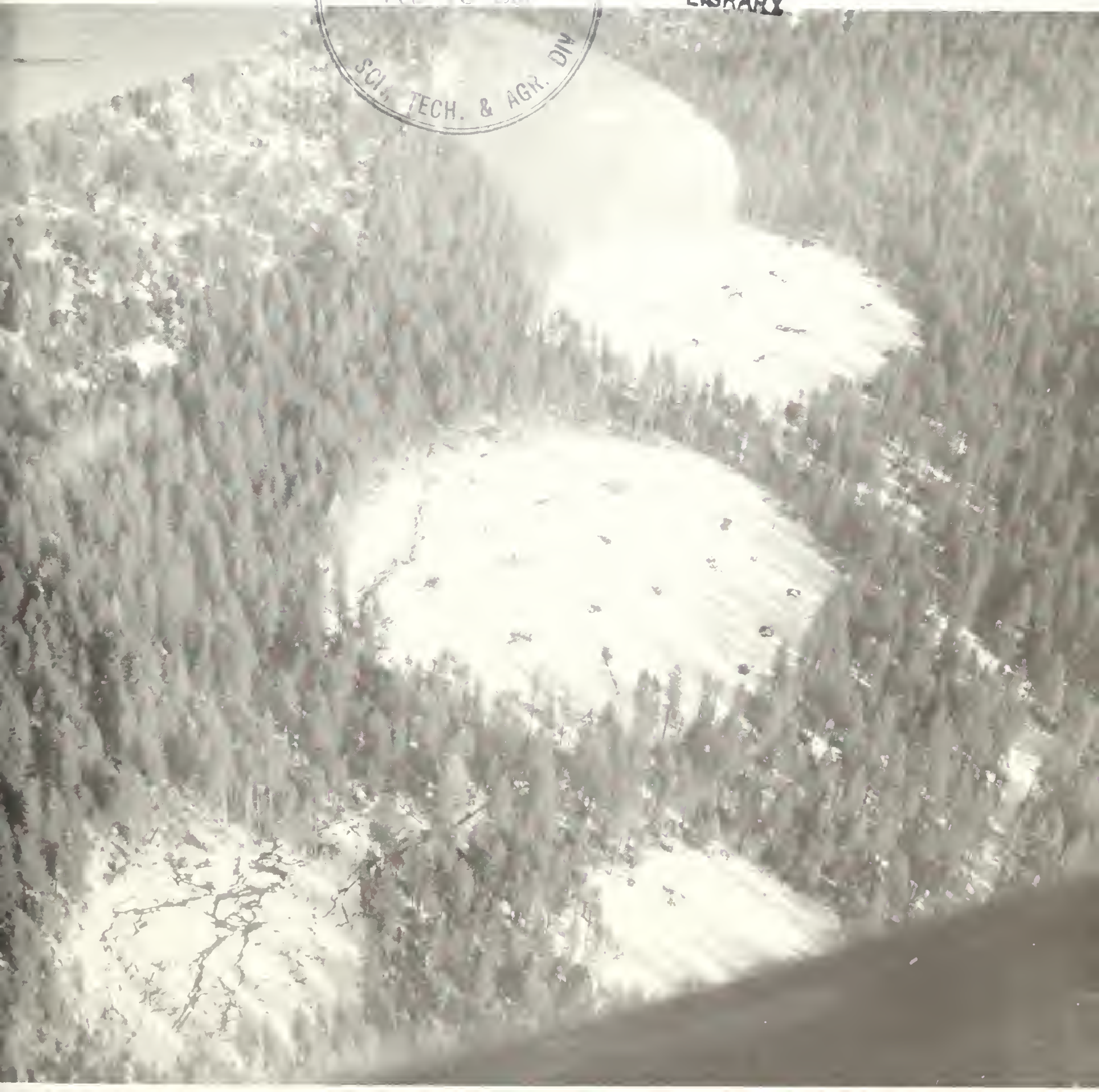
Research Paper
PSW-150

Seed Dissemination in Small Clearcuttings in North-Central California

Philip M. McDonald

GOVT. DOCUMENTS
DEPOSITORY ITEM
FEB 17 1981
CLEMSON
LIBRARY

CLEMSON UNI LIBRARY
FEB 1981
SCI., TECH. & AGR. DIV



Author:

PHILIP M. McDONALD is doing research on silviculture of Sierra Nevada forest types, with headquarters at Redding, California. A native of Seattle, Washington, he holds bachelor's (Washington State University, 1960) and master's (Duke University, 1961) degrees in forestry, and a Ph.D. in forest science (Oregon State University, 1978).

Cover: Aerial view of two 10-acre (4-ha) and two 2-acre (0.8-ha) circular clearcuttings on the Challenge Experimental Forest, Yuba County, California.

Publisher:

Pacific Southwest Forest and Range Experiment Station
P.O. Box 245, Berkeley, California 94701

January 1980

Seed Dissemination in Small Clearcuttings in North-Central California

Philip M. McDonald

CONTENTS

Introduction 1
Methods 1
Results 2
Discussion 3
Literature Cited 5

IN BRIEF...

McDonald, Philip M.
1980. **Seed dissemination in small clearcuttings in north-central California.** Res. Paper PSW-150, 5 p., illus. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

Retrieval Terms: seed production, seed dispersal, clearcutting, *Pinus ponderosa, Libocedrus decurrens, Pseudotsuga menziesii, Abies concolor,* Challenge Experimental Forest

As forestry becomes more intensively applied, the need for more and better silvicultural techniques and guidelines is paramount. Clearcutting is one technique that foresters in north-central California are considering.

In young-mature, mixed-conifer stands on good sites, regeneration in natural openings has been observed to be both scanty and abundant. Further, it seems to be distributed in other than a random pattern. Reasons for these observations are unknown, although two possibilities often are heard: "It is too hot for young conifers near the clearcut center" and "brush and weeds kill conifer seedlings and this is why there are so few."

Results of this study suggest that a third reason is operative: seedfall is highly variable and could be deficient especially near the center of clearcuttings.

On the Challenge Experimental Forest in Yuba County, California, seedfall was evaluated in 2-, 5-, and 10-acre circular clearcuttings cut specifically to study natural seedfall. Corners in square or rectangular compartments receive excessive and unpredictable amounts of seed and, therefore, are difficult to study. During this 1964–1967 study, 10 seed crops ranging from light to bumper were borne by ponderosa pine, white fir, incense-cedar, and Douglas-fir. A seed crop is defined as that produced by one species in 1 year. Seedfall ranged from 76 to 40,691 sound seed per acre (188 to 100,547/ha) for a single species in a given year.

Each opening was divided into concentric zones so that seedfall of each species could be quantified relative to distance from the forest edge. In general, seedfall decreased as distance into the opening increased. Some seeds of white fir and ponderosa pine reached the center of 10-acre clearcuttings, but the smaller seeds of Douglas-fir and incense-cedar did not.

Seedfall was examined in terms of the amount of seed that fell into the different-sized clearcuttings while the soil surface in them was loose and relatively free of vegetative competition. These seeds, and resultant seedlings that survived for 4 years, formed the basis for evaluating the adequacy of natural seedfall in the clearcuttings.

Despite increasing emphasis on planting genetically superior seedlings, regeneration of thousands of acres of forest land in the West will be from natural seeding for years to come. Before natural seedfall and natural regeneration can be predicted, however, knowledge of the frequency and magnitude of seed crops, and of seed flight distance must be available.

Natural seedfall of most conifer species in most parts of California has been studied for years, but that for young-mature, mixed-conifer stands in north-central California has not. Results of this investigation, therefore, contribute both to knowledge of seedfall capability for these species at a younger age, and to seedfall information for an area where data have not existed before.

Previous work on seed dissemination of the species studied here generally shows that the amount of seed on the ground decreases rapidly with distance from the producing tree. For ponderosa pine *(Pinus ponderosa* Laws.) in Idaho, most seed fell within 66 feet (20 m) of the tree (Curtis and Foiles 1961). In central Oregon, the quantity of ponderosa pine seed dispersed into a clearcutting dropped sharply with distance from the source (Barrett 1966). Nearly three times more seed fell on the sheltered border of the clearcutting than on the more exposed border. At 265 feet (81 m) into the clearcutting, seed quantity on the sheltered side was about seven times that of the exposed. At this distance, seedfall was one-fifth and one-twelfth of that falling near the respective sheltered and exposed edges of the clearcutting. Also in central Oregon, ponderosa pine seed dissemination varied with minor differences in topography (Dahms and Barrett 1975). Taller trees located above a clearcutting cast seed farther than those slightly below it. In general, seedfall beyond 200 feet (61 m) was only 2 to 3 percent of that near the timbered edge.

Gordon (1970) noted a strong tendency for white fir *(Abies concolor* [Gord. & Glend.] Lindl.) and California red fir *(Abies magnifica* A. Murr.) seeds to be dispersed by strong southwesterly storm winds. Seed on the easterly border, therefore, was blown back under the forest canopy. Gordon concluded that "seed dispersal over openings seems to be determined largely by amounts released at the windward cutting edge."

For Douglas-fir *(Pseudotsuga menziesii* [Mirb.] Franco), Roy (1960) noted that the number of sound seed delivered to the ground decreased rapidly with increasing distance from the source. Furthermore, he stated that "seed dispersal is dependent upon the pattern of gentle and strong winds and not upon the aerodynamic characteristics of seed."

This paper describes a 4-year (1964–1967) study of seedfall on the Challenge Experimental Forest in north-central California.[1] Research on this Forest is applicable to about 1.5 million acres (600,000 ha) of highly productive timberland along the lower west slopes of the Sierra Nevada. Tree species studied were ponderosa pine, white fir, Douglas-fir, and incense-cedar *(Libocedrus decurrens* Torr.). The trees were young-mature (90 to 120 years old) and relatively tall for their age (120 to 180 feet) because of the good site.

METHODS

Dominant and codominant trees of all species on the study site numbered about 35 per acre (86/ha), 70 percent of which were ponderosa pines. Trees in these crown classes produced more than 80 percent of a seed crop (McDonald 1973, 1976). Douglas-fir, younger than ponderosa pine, was more likely found in the intermediate and codominant crown classes than in the dominant class.

---

[1] This study was done in cooperation with the Soper-Wheeler Company, Strawberry Valley, California.

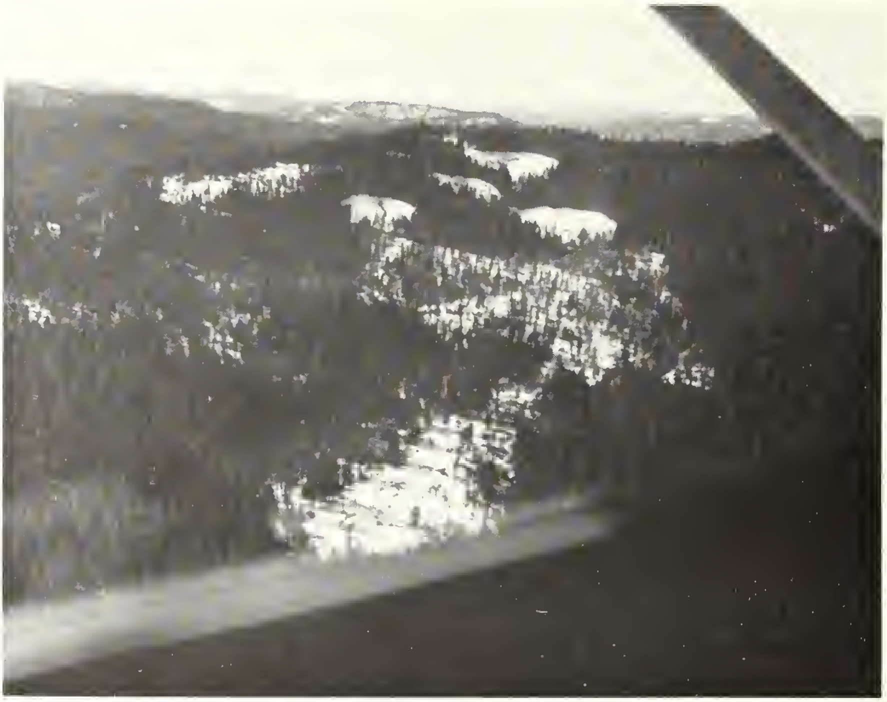


Figure 1—Aerial view of two 10-acre (4-ha) and two 2-acre (0.8-ha) circular clearcuttings on the Challenge Experimental Forest, Yuba County, California.

During the 4-year study, ponderosa pine seed crops rated as bumper in 1967, medium in 1964, and light in 1966. White fir produced medium crops in 1964 and 1967. Douglas-fir yielded light crops in 1964, 1965, and 1967, and incense-cedar bore only a few cones in 1965 and 1967.

To facilitate the study of natural seedfall, small circular areas of 2, 5, and 10 acres were clearcut *(fig. 1)*. Two clearcuttings of each size were located on a southwest aspect, and two of each size on a northeast aspect. Average slope on the southerly aspect varied from 5 to 15 percent, and on the northerly aspect from 10 to 35 percent. Relative positions of the clearcuttings on the slopes extended from near the top to near the bottom.

Each clearcutting was divided into zones. This division facilitated the quantification of seedfall at various distances into the clearcuttings. Zone 1 began at the forest edge and extended inward toward the clearcut center for 100 feet (30 m). Zone 2 extended inward 100 feet beyond that, and successive zones, if present, continued toward the plot center.

In each size of clearcutting the number of zones was:

Size *(acres)*	Radius *(feet)*	Zones
2	166	2
5	263	3
10	372	4

Sampling intensity was based on past experience with seedfall from a medium ponderosa pine seed crop, and adjusted by the proportionate area in each zone. Sampling was by foot-square (0.09 m^2) seed traps *(fig. 2)*, the reliability of which was ascertained earlier for the species being studied (McDonald 1973, Roy 1959). A polar coordinate (random bearing and distance) technique was used to place a total of 772 seed traps in the 12 clearcuttings. Each 10-acre clearcutting received 143 traps, each 5-acre opening 39, and each 2-acre clearcutting 11 seed traps. Scaled maps showed the location of each numbered seed trap in each opening.

Seed traps were cleaned before seedfall each autumn and emptied after seedfall each winter. Cutting tests assessed seed soundness. Only data for sound seed are provided in this paper.

RESULTS

Results of this study showed that seed distribution is highly variable and, in some instances, erratic. An overall finding, useful to land managers, is that 89 percent or more sound seeds of ponderosa pine, Douglas-fir, white fir, and incense-cedar fell within an area 1½ times the height of the average dominant tree.

Seedfall estimates ranged from 76 to more than 40,600 sound seed per acre for a given species in a given year *(table 1)*. Production of sound white fir and ponderosa pine seeds was particularly high in 1967 and only slightly less so in 1964. Although white fir trees made up only 3 percent of the dominant and codominant stand, they were especially fruitful.

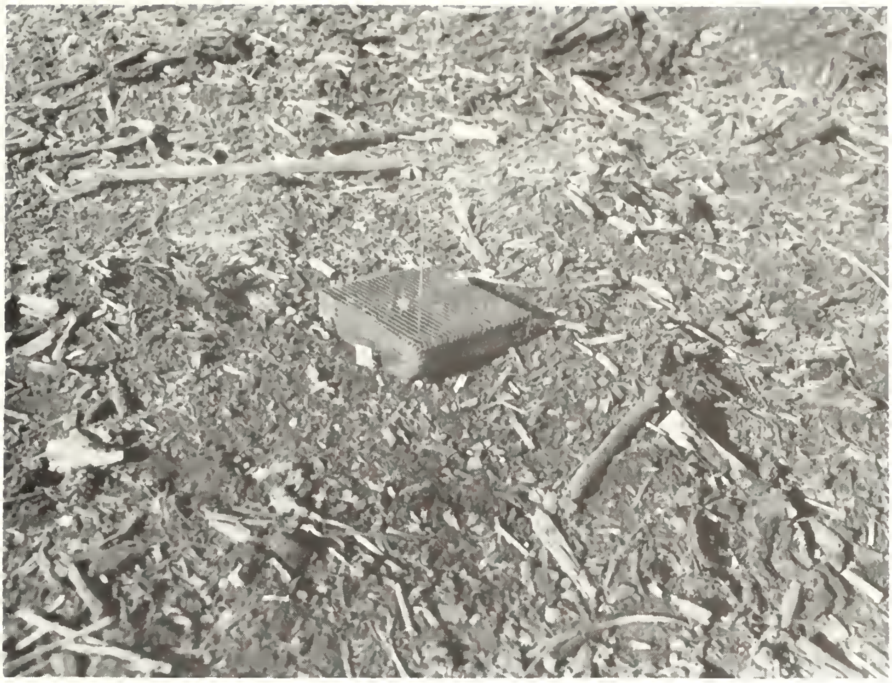


Figure 2—A 1-foot-square seed trap in place in a clearcutting on the Challenge Experimental Forest, Yuba County, California.

When seedfall data from all species for the 4-year study were analyzed by size of clearcutting and zone, the seed distribution pattern was revealed. Regardless of the size of the clearcutting, more sound seed fell on each acre of the outermost zone nearest the forest edge *(table 2)*. And each successive zone toward the center received less seed. The lowest number of seeds per acre consistently fell in the innermost zone in each size of clearcutting. In the innermost zone, total estimated seedfall was about 4350 sound seed per acre (10,751/ha); that next to the forest edge amounted to more than 20,100 sound seed per acre (49,763/ha).

The proportion of seed of each species that fell within an area 1½ times the height of the average dominant tree (200 feet) was:

Species	*Percent*
Douglas-fir	98
White fir	91
Ponderosa pine	89
Incense-cedar	100

To ascertain seed flight distance of the various species, sound seed per acre for each species in each zone was totaled for all seed crops in 5- and 10-acre openings. Zones receiving no sound seed of a given species were especially noted *(table 3)*.

At least some seed of the species having larger seeds—ponderosa pine and white fir—were found in all zones of 10-acre clearcuttings. Of the species having smaller seeds, Douglas-fir seed was disseminated into zone 3 but not into zone 4, and seed of incense-cedar was not distributed into either zone 3 or 4. In the 5-acre openings, no seed of Douglas-fir or incense-cedar reached zone 3.

Seedfall was examined further to assess the amount of seed that fell into the different zones of each size of clearcutting the first year of the study *(table 4)*. At this time (1964) seeds were falling on recently prepared ground. The soil was loose and friable, and nearly free of competing vegetation. Subsequent seed crops fell on increasingly harder ground, covered with a rapidly increasing diversity and abundance of grasses, forbs, and woody shrubs.

DISCUSSION

The study of seed distribution is difficult because many variables must be examined. These range from weight, shape, and aerodynamics of each species' seed to such meteorological considerations as windspeed and direction, relative humidity, and temperature. Position of the tree relative to the opening where the seed will be dispersed is also a variable. Trees on the edge of the opening have better opportunities for seed dispersal than those in the second and third ranks within the forest. The inherent height of the various tree species also is important. Topographic variables such as slope, aspect, and position of opening on the slope must be considered. Seldom, if ever, does any one variable act alone. Most often, the interaction of all of them governs seedfall. It is nearly impossible to isolate the effect of each vari-

Table 1—*Sound seed per acre by species and size of clearcutting for the years 1964 to 1967 on the Challenge Experimental Forest, Yuba County, California*[1]

Species	Crop year											
	1964			1965			1966			1967		
	Size of clearcutting *(acres)*											
	2	5	10	2	5	10	2	5	10	2	5	10
	Sound seed per acre											
Douglas-fir	1,985	560	534	0	560	382	0	0	0	0	0	0
White fir	2,978	5,599	2,595	0	0	0	0	0	0	32,751	4,199	7,325
Ponderosa pine	992	1,680	687	0	0	0	0	560	153	40,691	7,559	15,344
Incense-cedar	0	0	0	0	280	228	0	0	0	992	0	76
Total	5,955	7,839	3,816	0	840	610	0	560	153	74,434	11,758	22,745

[1] Values shown are the average for the four replications of each size of clearcutting.

Table 2—*Sound seed per acre by zones within clearcuttings for the years 1964–1967 on the Challenge Experimental Forest, Yuba County, California*[1]

Zone	Size of clearcutting *(acres)*			
	2	5	10	All
	Sound seed per acre			
1	67,488	10,864	9,160	20,139
2	12,902	9,518	6,030	7,560
3	—[2]	2,520	5,878	5,406
4	—	—	4,351	4,351
All[3]	58,775	9,942	7,395	14,189

[1] Values shown are the average for the four replications of each zone for each size of clearcutting. Zone 1 for all clearcuttings is nearest surrounding timber.

[2] Dashes indicate no zone present.

[3] These data were determined through weighting by zone areas.

Table 3—*Sound seed of all seed crops, by species, in each zone of the 10-acre clearcuttings for the yeas 1964 to 1967 on the Challenge Experimental Forest, Yuba County, California*

Species	Zone			
	1	2	3	4
Douglas-fir	1,832	1,832	305	0
White Fir	11,602	11,908	9,792	6,411
Ponderosa pine	22,597	18,321	13,435	10,993
Incense-cedar	610	610	0	0

Table 4—*Seedfall from 1964 seed crop, by zones, in 2-, 5-, and 10-acre clearcuttings on the Challenge Experimental Forest, Yuba County, California*[1]

Size of clearcuttings *(acres)*	Species	Zone			
		1	2	3	4
		Sound seed per acre			
2	Douglas-fir	992	992	—[2]	—
	White fir	992	1,985	—	—
	Ponderosa pine	0	992	—	—
5	Douglas-fir	0	560	0	—
	White fir	3,639	1,680	280	—
	Ponderosa pine	1,400	280	0	—
10	Douglas-fir	458	76	0	0
	White fir	763	840	687	305
	Ponderosa pine	305	153	229	76

[1] Values shown are the average for the four replications of each zone for each clearcutting. No incense-cedar seed were found.

[2] Dashes indicate no zone present.

able or of each interaction. And the instrumentation necessary to do the job is staggering.

Sampling seedfall is also difficult and expensive. Just physically installing an adequate number of seed traps is a big job.

Sampling design and intensity for seed trap placement were based on variances derived from previous samples for apparently comparable conditions. But seed distribution in the clearcuttings was more erratic than anticipated. Many traps caught no seed. Other traps, especially near the forest edge, caught a shower of seeds, and the large number of seeds per trap boosted sample variation to high levels.

As originally envisioned, statistical analysis was to be by regression, augmented by rank tests. These techniques proved to be unsuccessful. In general, these data, given their variable nature, were not adequate to allow statistical testing. Evaluations of the results, therefore, are statistically unsubstantiated. This fact, in spite of the large seed trap sample and initial concern with sampling design, leads one to question if studies like this are practical. Inherent high variation often necessitates a huge sample, and an unrealistically high budget.

Nevertheless, results show trends which should influence silvicultural treatments. Ten seed crops were produced in 4 years, and several of these crops rated at least medium in terms of seedfall. The land manager, therefore, can count on at least some seed falling relatively soon after cutting or site preparation. Quantifying each seed crop in terms of sound seed could be helpful to landowners contemplating natural reforestation. Because several species produced these seeds, a new stand composed of more than one species is possible. A useful overall finding is that 89 percent or more of sound seeds of ponderosa pine, Douglas-fir, white fir, and incense-cedar fell within an area 1½ times that of average dominant tree height, and, this fact agrees generally with results of other studies.

Additional findings from this study mostly concern seed distribution. The amount of sound seed distributed into clearcuttings of 2, 5, and 10 acres was highly variable *(table 1)*. However, a steady trend of decreasing seed with distance from the forest edge was evident *(table 2)*. Seeds of Douglas-fir and incense-cedar were not dispersed into the clearcuttings beyond 300 and 200 feet, respectively *(table 3)*. In support of *table 2*, a similar trend of decreasing seedfall with increasing distance toward the clearcut center for the seed crops of a given year was evident *(table 4)*. The difference in seed flight distance among species is in general agreement with Siggins (1933) who reported ponderosa pine seed to fall at a rate of 5.0 feet per second, white fir at 5.7 feet per second, and incense-cedar at 5.9 feet per second. Presumably, seeds that fall slowly have a greater potential for longer seed flight distance. With a slower rate of fall (4.4 feet per second), seed of Douglas-fir should travel farther into the clearcuttings. They did not however, because as noted earlier, trees of this species tend to be shorter with crowns in a more shielded position in the stand.

At least some seeds of ponderosa pine and white fir reach the center of 10-acre clearcuttings, however. Wind gusts, eddies, and possibly convectional lifting, aid in transporting them there. In artificially regenerated plantations they, and the seedlings which result, may or may not be desirable. If the plantation is understocked, more seedlings may be welcome; if fully stocked, eventual thinning may be necessary.

Whether or not the amount of sound seed falling into clearcuttings is adequate for successful regeneration is critical. Adequacy depends on what the landowner feels is sufficient (above the minimum standards of the California Forest Practice Act) and this, in turn, is related to management goals and productivity of the land.

An analysis of the numbers of seedlings established in this study, which are proportional to the number of seeds that fell, will be reported in another paper. In the 2-, 5-, and 10-acre clearcuttings, number of 4-year-old white fir seedlings ranged from 147 to 269 per acre (363 to 665/ha) and milacre stocking, which is a measure of seedling distribution over the landscape, varied from 12 to 18 percent. Similar values for ponderosa pine were 77 to 196 seedlings per acre (190 to 484/ha) with milacre stocking values of 7 to 17 percent. Douglas-fir and incense-cedar each had about 7 to 43 seedlings per acre and stocking of 1 to 4 percent. Seedling density of all conifer species ranged from 385 to 507 per acre (951 to 1253/ha) and milacre stocking of 24 to 35 percent.

From these kinds of data, land managers can choose seedling numbers, or seedling distributions, or both, to assess the effectiveness of natural seedfall in clearcuttings.

LITERATURE CITED

Barrett, James W.
1966. **A record of ponderosa pine seed flight.** USDA Forest Serv. Res. Note PNW-38, 5p., illus. Pacific Northwest Forest and Range Exp. Stn., Portland, Oreg.

Curtis, James D., and Marvin W. Foiles.
1961. **Ponderosa pine seed dissemination into group clearcuttings.** J. For. 59:766–767.

Dahms, Walter G., and James W. Barrett.
1975. **Seed production of central Oregon ponderosa and lodgepole pines.** USDA Forest Serv. Res. Paper PNW-191, 11 p., illus. Pacific Northwest Forest and Range Exp. Stn., Portland, Oreg.

Gordon, Donald T.
1970. **Natural regeneration of white and red fir . . . influence of several factors.** USDA Forest Serv. Res. Paper PSW-58, 32 p., illus. Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif.

McDonald, Philip M.
1973. **Cutting a young-growth, mixed-conifer stand to California Forest Practice Act standards.** USDA Forest Serv. Res. Paper PSW-89, 16 p., illus. Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif.

McDonald, Philip M.
1976. **Shelterwood cutting in a young-growth, mixed-conifer stand in north central California.** USDA Forest Serv. Res. Paper PSW-117, 16 p., illus. Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif.

Roy, D. F.
1959. **Small seed traps perform well in the Douglas-fir type of California.** U.S. Forest Serv. Pacific Southwest Forest and Range Exp. Stn., Res. Note 150, 7 p., illus. Berkeley, Calif.

Roy, Douglass F.
1960. **Douglas-fir seed dispersal in northwestern California.** USDA Forest Serv. Tech. Paper 49, 22 p., illus. Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif.

Siggins, Howard W.
1933. **Distribution and rate of fall of conifer seeds.** J. Agric. Res. 47(2):119–128, illus.

The Forest Service of the U.S. Department of Agriculture

...Conducts forest and range research at more than 75 locations from Puerto Rico to Alaska and Hawaii.

...Participates with all State forestry agencies in cooperative programs to protect and improve the Nation's 395 million acres of State, local, and private forest lands.

...Manages and protects the 187-million-acre National Forest System for sustained yield of its many products and services.

The Pacific Southwest Forest and Range Experiment Station

...Represents the research branch of the Forest Service in California, Hawaii, and the western Pacific.

McDonald, Philip M.
1980. **Seed dissemination in small clearcuttings in north-central California.** Res. Paper PSW-150, 5 p., illus. Pacific Southwest Forest and Range Exp. Stn., Forest Serv., U.S. Dep. Agric., Berkeley, Calif.

In a 1964–1967 study on the Challenge Experimental Forest, seedfall was evaluated in 2-, 5-, and 10-acre circular clearcuttings. During the 4 years, 10 seed crops, ranging from light to bumper, were produced by ponderosa pine, white fir, Douglas-fir, and incense-cedar. Seedfall ranged from 76 to 40,691 sound seed per acre (188 to 100,547/ha) for a single species in a given year. From 89 to 100 percent of each species' seed fell within an area 1½ times the height of the average dominant tree. Overall, seed distribution was highly variable.

Retrieval Terms: seed production, seed dispersal, clearcutting, *Pinus ponderosa, Libocedrus decurrens, Pseudotsuga menziesii, Abies concolor,* Challenge Experimental Forest